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George C. Marshall Space Flight Center
Huntsville, Alabama

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SUMMARY

This report describes the results of long range acoustic propagation studies which were performed by personnel of General Mills, Incorporated, and the Test Division of the George C. Marshall Space Flight Center. Since the Saturn Vehicle comprises probably the largest manmade source of steady-state low frequency sound, such studies have been necessary to avoid irritation and possible actual damage from such sound in the surrounding civilian areas. The existent meteorological conditions during the test firing determine the path (or paths) which the sound energy will take and, thereby, the resulting overall sound pressure levels at long ranges. One objective has been to formulate the problem in more exact terms and to assess magnitude of the rises in sound pressure level within areas subject to meteorological focusing. Another objective was to determine those meteorological conditions under which space vehicle testing could be performed with little or no disturbance outside MSFC. Under this second objective, it was seen that the ability to utilize routine wind and temperature measurement techniques along with long range weather forecasts would provide information which would be useful in scheduling static tests of the large space boosters. Consequently, the data potential of rawinsonde, double theodolite, and other more specialized types of meteorological measuring systems were evaluated.

Measurement data are presented showing the effect of weather upon the overall sound pressure level resulting from rocket engine tests at ranges up to ten miles. Data are also shown giving measured rises in sound levels resulting from different focal conditions.

Some of the included Sections were taken from "Feasibility Study of An Aerocap Supported Meteorological Measuring System" which was written for Marshall Space Flight Center by General Mills personnel under Study Contract NAS8-1634.

SECTION I. INTRODUCTION

One of the byproducts of static tests of large space vehicles, such as the Saturn, has been a large generated sound pressure level. When this sound is either attenuated within the missile area or is somehow directed up away from the earth, there has been little annoyance in the surrounding civilian communities. Under some meteorological conditions, this sound is brought back to the ground in those areas and it is actually magnified as though the atmosphere were a large lens.

In the past, this effect has rarely been of interest because of the limited signal strengths which it was possible to sustain over appreciable periods. Since the development of the large rocket engine, this refractive effect has assumed greater importance. At Marshall Space Flight Center, these acoustical focusing problems have been of special interest because of the proximity of the city of Huntsville, Alabama. The city is on the north and east boundaries of Redstone Arsenal about 5 to 12 miles from the Saturn Test Tower.

Meteorologically, the MSFC-Huntsville area is dominated by a general westerly-southwesterly prevailing wind pattern. During the winter months, this pattern intensifies and is quite often accompanied by a strong surface inversion. This causes meteorological focusing toward the city. Such conditions do not occur every day nor do they often last more than a few hours. Nevertheless, examination of the past meteorological data shows that such focusing conditions may exist for varying lengths of time during any season or month. The studies encompassed by this report include both theoretical and empirical approaches to the solution of this problem.

SECTION II. SOUND PROPAGATION CHANGES RESULTING FROM METEOROLOGICAL FACTORS

A. DESCRIPTION OF THE PROBLEM

One aspect of static firing tests involving the Saturn booster rocket has been the production of very high levels of acoustic noise. In effect, a sound source with sound pressure levels of 160 db or higher is created which continues over an operational period of approximately two minutes. Results from field surveys of sound during the initial series of static tests have shown that the acoustic power radiated from eight-engine tests ranges from 25 to 40 megawatts, that the frequency spectra peaks between 10 to 100 cps, and that the directivity is quite broad (as compared to a much sharper pattern of directivity noted during the two and four-engine tests) (Ref.1). Noise causing the greatest problem in the Huntsville area has a frequency below 50 cps; noise at a frequency of 2 cps has been detected 700 miles away.

Under certain unfavorable conditions of sound propagation, those sound rays emanating from the source at angles with the horizontal up to 15 degrees or more can be refracted such that they not only impinge upon the ground at considerable distances but focus a seriously high level of sound return upon a relatively small area. Thus, on occasion, propagated sound from the Saturn tests has produced annoyance and alarm at a range of 10 miles or more within the city and suburbs of Huntsville.

Despite the establishment of a standard forecast routine by MSFC personnel in order to suspend firings during conditions of adverse sound propagation, the results have not attained the desired level of reliability. Therefore, various improvements are actively being sought, primarily in terms of increased quantity and quality of input data, more rapid calculation of sound ray patterns with automatic computers, and direct probing of sound propagation conditions using artificial sound sources with a down-range array of microphone pickups.

Although the primary concern, during this study program, has been the improvement of the meteorological data input in terms of their application to conventional sound forecast techniques, some attention has also been devoted to the more unique aspects of the problem. For example, most of the available literature concerned with field studies of sound propagation has dealt with explosive sound sources or with continuous, but moving, sound sources such as airplanes. The Saturn booster static firings, however, provide a fixed continuous sound source over a period of approximately two minutes. In addition, the rocket exhaust introduces a significant quantity of heat and momentum into the atmospheric environment, which, although rapidly diffused, may conceivably produce (by the end of the test period) an appreciable change in the overall pattern and local intensity levels of the sound return. Thus, any attempt at continuous micrometeorological determinations of the undisturbed wind and temperature environment would be quite fruitless if the rocket exhaust were to produce a temporarily strong refracting layer whose effects upon sound propagation would considerably exceed those produced by natural short-term variations in the sound velocity profile.

Another important effect peculiar to the Saturn test problem is the influence of hilly terrain upon the propagation and modification of sound ray patterns. No experimental field program has ever been designed or carried out which would specifically identify and isolate terrain factors from the more usual effects of refraction and attenuation. The mere physical presence of isolated hills or ranges of hills can be expected to produce direct effect upon the wind circulation. For example, terms of convergent channeling between terrain barriers would be affected. In addition, there are more subtle thermodynamic effects associated with the diurnal cycle of solar heating. The unequal absorption of solar energy upon hill slopes and adjacent valleys can give rise to thermally induced micro-scale pressure systems, which can significantly change the broad-scale wind pattern at least within the lower several hundred feet of the atmosphere. This latter type of effect is well evidenced by the well known mountain-valley circulation, characterized by valley (up-slope) breezes through the day and mountain (down-slope) breezes during the night. The only adequate basis for the study of terrain effects would be to establish an experimental data measuring network at several carefully selected down-range positions.

B. GENERAL APPROACHES TO THE PROBLEM

The most immediately useful approach to the sound propagation problem is to improve the capability for short-period prediction. The term "short-period prediction" is defined as the type of persistence forecast technique currently used by MSFC, wherein it is assumed that the sound propagation pattern computed from very recent rawinsonde data will not undergo significant change during the time interval prior to the test firing. Possible areas of improvement involve the use of radiosonde flight units modified to increase their sensitivity over the first 10,000 feet, the use of slower ascent rates to permit more detailed determination of wind and temperature shears, and the selection of balloon release points which would produce the most representative sampling of temperature and wind data.

There also would appear to be the necessity for developing a standard procedure to make 24-hour forecasts of sound propagation conditions. Reliable forecasts of this kind would be of great value in scheduling standby test alerts. An input of surface and upper air data would be required from a surrounding network of stations within at least a 1000-mile radius. The requisite rawinsonde data are already available on the standard teletype and facsimile circuits and could either be used with objective regression formulas or evaluated by professional meteorologists to determine the 24-hour forecasts.

A more basic approach to the problem would involve the establishment of a mobile micrometeorological network to be used as a supplement to the rawinsonde observation program and for specialized studies. For example, it would be especially interesting to measure the disturbance produced by the rocket exhaust upon the three-dimensional sound velocity field. One possible approach might involve a network of sensors on small captive balloons to record the changes in temperature and wind speed occurring at selected down-range positions during the actual firing tests. It might be possible, in this way, to correlate the detailed pattern of vertical and horizontal sound velocity variation with the observed changes in the sound return levels at various ground microphones. Other possible applications of the mobile network might include simultaneous measurements of the wind field at selected locations and to study terrain effects during different types of prevailing wind circulations. This type of study could be carried out on days when no firings are scheduled, so as to take advantage of the small captive balloon network. The study of terrain wind effects could be profitably augmented by making double theodolite wind soundings whenever possible. This would facilitate measurement of the wind directions and aid in checking the wind speeds measured by the captive balloons. Another application of the double theodolite network might be to carry out a continuous series of wind soundings whenever cloudless conditions permit. This would be done on days of scheduled firings. Slow ascent balloons would enable a very accurate measurement of the wind field from the surface to 10,000 feet and these data could then be compared with the winds measured by the GMD-1 unit. Other possible types of specialized studies include using the captive balloon network to suspend microphones for measuring the sound return at various elevated points from artificial sound sources.

Specialized research studies, such as those listed above, would not only lead to a better understanding of sound propagation phenomena, but could conceivably result in the development of empirical correction factors for improving the short-period forecasts. Although it is realized that a fair-sized staff of qualified personnel would be required to operate these special data gathering programs, the opportunity to examine the unique properties of such a large continuous sound source (as provided by the Saturn booster) should not be lost.

C. CLASSICAL SOUND PROPAGATION THEORY

There are several reviews of the influence of meteorological conditions on sound propagation in the lower atmosphere, including those by Tedrick (Ref.2), Cox (Ref.3), and Nyborg and Mintzer (Ref.4). Discussions of the basic theory of sound propagation also appear in published accounts of experimental field studies, including those dealing with rocket noise by Cole et al. (Ref. 5), with airplane noise by various scientists of Armour Research Foundation (Ref. 6, 7, and 8), and with artillery shell firings by Rothwell (Ref. 9 and 10).

Actual sound fields which exist in typical out-of-door situations are almost prohibitively difficult to describe in detail. The atmospheric medium for sound transmission is never homogeneous or quiescent, and the boundary conditions are often quite complicated in terms of contour, vegetative covering, and manmade structures. Nevertheless, it is possible to treat the problem in an approximate way by considering the following principal elements of sound propagation theory: (1) attenuation by spherical divergence, or the spreading out of the wave front, (2) attenuation due to absorption processes in the air, (3) attenuation due to ground effects along the earth boundary, and (4) attenuation by refraction of sound waves resulting from spatial variations in air temperature and wind. The most important aspect of sound propagation, in terms of the Saturn noise problem, is the refraction effect, which not only is responsible for bending the sound rays back to the earth's surface but often results in "focus" areas of concentrated sound energy return.

If the attenuation is first considered, by spherical divergence, the loss in decibels of the sound level at point P (at a distance R from the source) relative to that at a reference point P_o (at a distance R_o from the source) is expressed by the quantity 20 $\log_{10}$ (R/R_o), which is a consequence of the inverse first power law

$$P = A/R$$

where P is the sound pressure amplitude and A is a constant. In the absence of other effects, such as refractive focusing of sound engery, the sound level will decrease by 20 db for each ten-fold increase in R from a chosen reference point. Expressed another way, there is a loss of 6 db each time R doubles.

The attenuation due to atmospheric absorption is comprised of: (1) "classical" absorption, produced by viscosity, conduction, diffusion, and radiation effects, (2) molecular absorption, which strongly depends upon the humidity, and (3) eddy attenuation, due to turbulent fluctuations in the wind structure. The effect of classical absorption is negligible, and at the lower audible frequencies of concern in this study, the molecular absorption (which depends upon the second power of the sound frequency) is quite weak. Under typical atmospheric conditions the sound loss due to molecular absorption is approximately 1 db per 5 miles at 30 cps and ten times as high at 300 cps. The eddy attenuation, which varies with the eddy size and turbulent energy of the wind field, is especially important within the first several hundred feet of the friction layer, where its effect is essentially the same in all directions. The effect of turbulent eddies is to scatter sound into shadow zones and somewhat blur the clear outlines of the classical sound ray patterns. However, few field measurements are available which are directly applicable to our problem. Measurements of wind eddy fluctuations from meteorological towers and captive balloon instruments would appear to be quite essential in the quantitative determination of sound levels received at the ground. This is especially true for sound rays whose path is primarily confined to the friction layer.

The ground attenuation can be calculated from a knowledge of the acoustic properties of the surface boundary layer, in addition to the sound frequency, the heights of the source and receiver, and the horizontal component of the source-receiver distance. The general expression for the sound pressure at any point is rather complicated. However, for the special case in which the source and receiver are both very near the ground, the ground is absorbing, and the distance is sufficiently great, the sound pressure is proportional to the inverse square of the distance (Ref. 4). In certain instances, the sound loss due to ground attenuation is comparable to that resulting from spherical divergence.

For the purposes of this study, the most important effect is the refraction of sound waves due to changes in the vertical profile of sound velocity, since the major objective at the present time is to predict the areas of high sound return and not to determine detailed isopleths of the forecast sound levels. Since the sound velocity in air depends upon temperature, humidity, and wind, it is the variation of these factors, with altitude, which determines the vertical sound velocity gradient and ultimately the refraction of sound waves. If we first consider the effects of temperature and humidity, the sound speed, C, in still dry air is given by LaPlace's equation

$$C = K \sqrt{T^*}$$

where T^* is the virtual temperature in degrees Kelvin and K is a constant (38.98 for C in knots and 65.84 for C in ft per sec). The virtual temperature is defined as that temperature necessary for the density of a parcel of dry air to equal that of moist air under the same pressure. Virtual temperature is related to the actual temperature, T, by the following expression:

$$T^* = \frac{T}{1 - 0.377 \frac{e}{p}}$$

where e is the water vapor pressure and p is the total pressure. Over the pressure range from 1000 to 700 mb (approximately the surface to 10,000 feet), the difference (T^* - T) for saturated air is 0.5 - 0.8°C at T = 0°C, 1.3 - 1.8°C at T = 10°C, 2.6 - 3.7°C at T = 20°C, and 4.9 - 6.1°C at T = 30°C. In practice, the humidity effect upon sound speed can generally be ignored without serious error (especially during the winter season outside the tropics).

The sound velocity at a fixed point in terrestrial space is a vector quantity made up of two components: (1) a vector whose magnitude is given by C, the sound speed, and whose direction is normal to the wave front at the point, and (2) the vector wind at the point. The vertical component of the wind velocity is customarily neglected. Furthermore, horizontal gradients of temperature and wind are usually assumed to be negligible over the area affected by the sound source.

Conventional analysis of sound refraction depends upon the concept of sound rays, which are defined as a curve such that the tangent at each point is in the direction of the resultant sound velocity. The main transport of sound energy takes place along these rays and the divergence or convergence of rays indicates decreasing or increasing energy concentration.

Following Cox et al. (Ref. 11), the refraction equation for sound rays states that for rays inclined but slightly to the wind

$$C + \mu_i \cos\theta = A_i \cos\theta$$

where θ is the inclination of the sound ray from the horizontal; μ_i is the component of the wind velocity in a given direction; and A_i, constant for any specific sound ray, is the velocity of the intersection of the wave front with the horizontal. Since the wind velocity seldom exceeds 10 percent of the sound speed within the first 10 to 15,000 feet of the troposphere, the refraction equation may be approximated by introducing a new term V_i defined by $V_i = C + \mu_i$, so that

$$V_i \approx A_i \cos\theta,$$

a simple version of Snell's law. Thus, toward any chosen azimuth from the sound source, the elevation angle of the sound ray, at altitude h, is related to the starting elevation of the ray, θ_o, according to the formula

$$V_h \sec\theta_h = V_o \sec\theta_o,$$

When the sound velocity decrease with height, the ray angle increases and the sound ray paths may be represented by a secant function. If the sound velocity increases with height, the ray angles decrease downward. Ray paths can be considered as segments of circles, all having the same curvature dV/V dh, over altitude intervals where the velocity gradient is constant with altitude. When the value of sound velocity at the earth's surface exceeds all values at higher altitudes, no surface sound return will occur. For a ray to be refracted to the surface from any upper layer, the maximum velocity attained in that layer must exceed the velocity at all points in the medium nearer the surface of the ground.

It should be realized that the usual applications of classical sound ray analysis involve various assumptions which may not be entirely justified (aside from simplifying the computational methods). The neglect of vertical velocity can be a serious shortcoming in those cases where natural or artificial convection, or orographical effects produce significant vertical velocity components of the order of 1 mps or more. The neglect of humidity is usually justified under most winter conditions in the Huntsville area. The necessity for layer analysis is brought about by the nature of available meteorological information; in particular, the winds, which are customarily calculated at 1000-foot intervals (although averaged over 2000-foot strata). Ideally, the wind profiles would be first determined from values averaged over intervals of 500 feet or less and then suitable combinations made of adjacent segments which are sufficiently similar. The assumptions of time invariance (over 1 to 2 hours) and of space invariance (over a scale of 10 to 15 miles in a region of hilly terrain) in the sound velocity profiles are viewed as perhaps the most serious limitations.

Therefore, there may be no more practical solution than to apply a probabilistic form of safety factor.

D. PREVIOUS APPLICATIONS OF SOUND FORECAST TECHNIQUES

Apparently the first standardized technique ever established to forecast tropospheric sound-wave propagation was that described by Cox et al. (Ref. 11). The purpose of this forecast program was to avoid shock damage to surrounding areas resulting from test shots of nuclear fission devices at the AEC Nevada Proving Ground. Data input consisted of forecast values of temperature and wind velocity at selected levels throughout the entire troposphere. The first step was to compute the sound speed at each level where a meaningful temperature forecast could be made; then the wind velocity component was computed in each direction of interest, on the basis of wind vector forecasts, at selected elevations. The wind component values were then added algebraically to the sound speeds in order to determine the total sound velocity profile for each of the chosen directions from the test site. Simple computational methods were used to determine the limiting range of returning rays whenever the profiles contained three or less significant segments. A more elaborate ray-plotting method of tabular computation was used to handle more complex structures of the sound velocity profile. Since no details were provided as to the methods used to predict the temperature and wind values, it is assumed that normal techniques of map analysis and extrapolation were employed. The entire sound ray forecast procedure was described as having worked quite successfully. The principal limitation of this technique lies in the long time period or large staff required for hand computation, if the analyses were to be carried out at close intervals of azimuth angle and sound ray angle.

More recently, two reports (Ref. 12 and 13) from the Ballistic Research Laboratories at Aberdeen Proving Ground have outlined the theoretical background and operational description of an electronic ray tracing technique which uses an analog computer. On the basis of standard ray theory, the computer is able to handle sound velocity profiles containing up to twenty gradient segments and present the resulting ray paths on a screen. If a focus should occur, it will be seen on the screen where the rays converge and the distance from the source will be shown. A library of 32 "typical" sound velocity profiles and their associated ray patterns are most commonly used for daily forecasts, although the computer is used for those special cases for which there is no matching profile.

In terms of long period forecasts, the BRL scientists state: "The direction of the winds is determined by the position of the high and low pressure areas in the atmosphere and with a little experience in this procedure a study of the daily weather maps will permit a meteorologist to forecast good shooting periods several days in advance." This statement is viewed as unduly optimistic since the forecast accuracy, in general, deteriorates rather rapidly as 24-hour forecasts can be characterized as good, 48-hour forecasts as fair, and forecasts for 72 hours and more are essentially worthless in terms of predicting significant departures from climatological normals.

The upper air wind and temperature information at Aberdeen Proving Ground is obtained by a GMD 1A rawinsonde observation made two or three hours before the scheduled firing. The reduced data are recorded at intervals of 500 feet from the ground surface to 5000 feet and at intervals of 1000 feet from 5,000 to 12,000 feet altitude. The data reduction technique for obtaining the winds at these intervals is not described. However, if the standard technique of two-minute averaging is employed and the normal ascent rate of approximately 1000 ft per min is also used for the rawinsonde flight unit, the 500 or 1000-foot wind shears would not be truly representative of this small vertical increment and would, in fact, be quasi-linear interpolations of the larger scale shear to which the observational method and data reduction technique are inherently limited.

The more recent BRL report (Ref. 13) lists five representative types of sound velocity gradients and the increase in sound intensity expected at the focus area associated with each type. The increase in intensity is expressed in terms of a multiplication factor. Perhaps a more meaningful expression of sound intensity increase appears in a current report dealing with launch site criteria for high-thrust rocket vehicles (Ref. 14), wherein the possible reinforcements of sound energy are expressed in decibels. The five typical sound velocity gradients and the possible sound intensity increase associated with each are as follows:

Sound Velocity Profile Type	Additive Sound at Focus
1. Single negative gradient	0
2. Single positive gradient	+14 db
3. Zero gradient near surface with positive gradient above	+20 db
4. Weak positive gradient near surface with strong positive gradient above	+28 db
5. Negative gradient near surface with strong positive gradient above	+40 db

The electronic ray tracing technique represents a striking advance in the art of sound propagation prediction; mainly because of its capability to analyze even the most complex forms of sound velocity profile. Instrumental and personnel requirements are quite modest and results have apparently been very satisfactory. The limitations inherent in their current method of wind determination, using the GMD-1A tracking unit along with standard operational and data reduction procedures, have apparently not resulted in significant error in predicting the range and intensity of focal areas. However, it must be pointed out that the relatively low acoustic levels of their explosive sound sources pose a more simple problem compared to that resulting from the Saturn firings, where a very intense noise is generated over a period of some two minutes. For this reason, the selection of favorable conditions for the Saturn tests is a much more critical problem and the meteorological data requirement is increased both in terms of quantity and quality.

SECTION III. DERIVATION OF BASIC SOUND RAY PROPAGATION EQUATIONS

Equations used in predicting the behavior of sound rays must be congruent with the method of obtaining the necessary meteorological data. Therefore, a linear sound velocity gradient must be assumed to express the change in velocity for a change in altitude. This gradient is stated algebraically as

$$K = \frac{dV}{dy} \tag{1}$$

where

K = velocity gradient in $\left(\frac{ft}{sec}\right)\left(\frac{1}{ft}\right)$

V = velocity in ft per sec

y = altitude in ft

Since the atmosphere is divided into different layers, throughout which these velocity gradients exist, it follows that a velocity V at an altitude y can be expressed by

$$V = V_n + K_n (y - y_n) \tag{2}$$

when

$$y_{n+1} \geqq y \geqq y_n$$

where

y_{n+1} = altitude at the start of the "n + 1" layer in feet

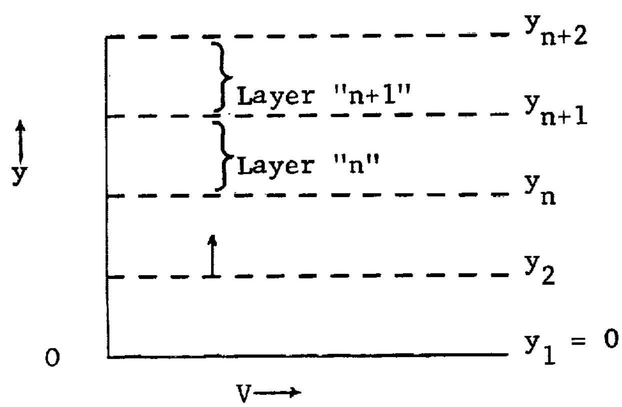
y_n = altitude at the start of the "n" layer in feet

V_n = velocity at the start of the "n" layer

K_n = velocity gradient existing throughout layer "n" in

$\left(\frac{\text{feet}}{\text{sec}}\right) \quad \left(\frac{1}{\text{feet}}\right)$

The following will illustrate clearly the nomenclature of the atmospheric layers:



Using equation (2) to calculate the velocity, V_{n+1}, existing at altitude, y_{n+1}, we have

$$V_{n+1} = V_n + K_n (y_{n+1} - y_n) \tag{3}$$

which implies that in solving for the characteristics of the sound rays, $y_1 = 0$ would be used as the starting point and procedure continued upward to increasing altitudes.

Rearranging equation (2), it is seen that

$$V = (V_n - K_n y_n) + K_n Y$$

and defining

$$S_n = V_n - K_n y_n$$

equation (4) is obtained as

$$V = S_n + K_n y \tag{4}$$

where

$$y_{n+1} \geqq y \geqq y_n$$

From Snell's law for the propagation of a sound ray, it is known that the velocity of the intersection of the wave front with the horizontal or x-axis is a constant known as Snell's constant, or for these purposes:

$$A = \frac{\cos \theta_p}{V_p} = \text{Snell's constant} \tag{5}$$

where

θ_p = angle the velocity V_p makes with the horizontal at any point "p" along the ray path

V_p = velocity at point "p"

and since A is a constant at any point on the ray path

$$A = \frac{\cos \theta_1}{V_1} = \frac{\cos \theta_n}{V_n} \tag{6}$$

where

θ_1 = angle the ray makes with the horizontal at $y = y_1 = 0$ or the ray's initial elevation angle

V_1 = velocity at $y_1 = 0$ or the initial velocity of the sound ray

θ_n = angle the ray makes with the horizontal at $y = y_n$

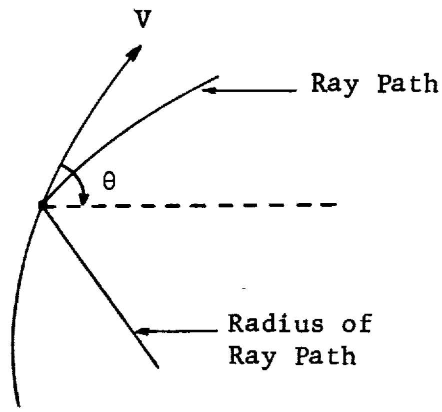
Since V is the velocity of the sound as it travels along its ray path, it is expressed by

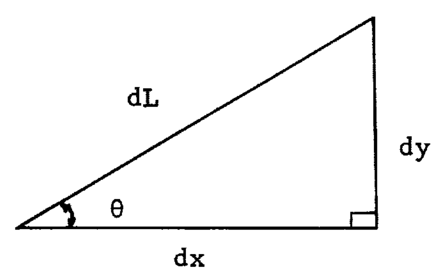
$$V = \frac{dL}{dt}$$

where

dL = increment of length of the ray path

dt = increment of time





From the above figures, it is seen that

$$\frac{dx}{dL} = \cos\theta$$

and

$$\frac{dy}{dL} = \sin\theta$$

Also, by definition

$$V_x = \frac{dx}{dt} = \text{velocity component in x direction}$$

and

$$V_y = \frac{dy}{dt} = \text{velocity component in y direction.}$$

From these expressions, it is simple to derive a relationship for y, x, t, and L (where L is the total length of the ray path) in terms of the velocity, since

$$V_y = \frac{dy}{dt} = \frac{dy}{dL}\frac{dL}{dt} = V\sin\theta \tag{7}$$

From trigonometric relationships

$$\sin \theta = \sqrt{1 - \cos^2 \theta}$$

and substituting in equation (7)

$$V_y = V \sqrt{1 - \cos^2 \theta} \tag{8}$$

Rearranging equation (5), it is seen that

$$\cos \theta = AV$$

or substituting in equation (8)

$$V_y = V \sqrt{1 - A^2V^2} \tag{9}$$

rearranging

$$\frac{dy}{V \sqrt{1 - A^2V^2}} = dt \tag{10}$$

then differentiating equation (4)

$$dV = K_n \, dy$$

where

K_n = a constant in the "n" layer

or

$$dy = \frac{1}{K_n} dV$$

substituting in equation (10)

$$\frac{dV}{V \sqrt{1 - A^2V^2}} = K_n \, dt$$

and upon integrating, the following expression is obtained.

$$K_n t = l_{n_e} \left(\frac{1 + \sqrt{1 - A^2 V^2}}{AV} \right) + C_1 \tag{11}$$

where

C_1 = constant of integration.

To solve for C_1, it is seen that when $t = t_n$; $V = V_n$ or upon substituting in equation (11)

$$C_1 = K_n t_n - l_{n_e} \left(\frac{1 + \sqrt{1 - A^2 V_n^2}}{AV_n} \right)$$

Substituting for C_1 in equation (11),

$$t = t_n + \frac{1}{K_n} \ln_e \left[\frac{V(1 + \sqrt{1 - A^2 V_n^{\,2}})}{V_n \, (1 + \sqrt{1 - A^2 V^2})} \right] \tag{12}$$

and letting $t = t_{n+1}$ and Δt_n equal the time required for the sound ray to pass through layer "n". Then Δt_n can be calculated as,

$$\Delta t_n = t_{n+1} - t_n = \frac{1}{K_n} \ln_e \left[\frac{V_{n+1} \, (1 + \sqrt{1 - A^2 V^2})}{V_n \, (1 + \sqrt{1 - A^2 V^2_{n+1}})} \right] \tag{13}$$

Returning to the expression for V_x, it is seen that

$$V_x = \frac{dx}{dt} = \frac{dx}{dL} \frac{dL}{dt} = V \cos \theta \tag{14}$$

or

$$V_x = AV^2 = \frac{dx}{dt}$$

Solving for dt,

$$dt = \frac{dx}{AV^2}$$

Substituting in equation (10),

$$\frac{dV}{V\sqrt{1 - A^2V^2}} = \frac{K_n dx}{AV^2}$$

or rearranging

$$K_n\, dx = \frac{AVdV}{\sqrt{1 - A^2V^2}} \tag{15}$$

Integrating equation (15),

$$AK_n x = -\sqrt{1 - A^2V^2} + C_2 \tag{16}$$

To solve for C_2, when $x = x_n$, then $V = V_n$ and,

$$C_2 = AK_n x_n + \sqrt{1 - A^2V^2}_n$$

Substituting in equation (16),

$$x = x_n + \frac{1}{AK_n}\left(\sqrt{1 - A^2V^2}_n - \sqrt{1 - A^2V^2}\right) \tag{17}$$

then letting $x = x_{n+1}$ and Δx_n equal the horizontal component of the distance traveled by the sound ray as it passes through layer "n", the following expression is obtained,

$$\Delta x_n = x_{n+1} - x_n = \frac{1}{AK_n}\left(\sqrt{1 - A^2V^2}_n - \sqrt{1 - A^2V^2}_{n+1}\right) \tag{18}$$

To derive the expression ΔL or the increase in the total length of the sound ray path as it passes through layer "n", we recall that

$$dy = dL \sin\theta = dL\sqrt{1 - A^2V^2}$$

and rearranging

$$dL = \frac{dy}{\sqrt{1 - A^2V^2}}$$

But equation (1) states that

$$dy = \frac{1}{Kn} dV$$

so,

$$K_n dL = \frac{dV}{\sqrt{1 - A^2V^2}} \tag{19}$$

Integrating equation (19), it is found that

$$L = - \frac{1}{AK_n} \cos^{-1} AV + C_3$$

and when $L = L_n$, then $V = V_n$, so

$$C_3 = L_n + \frac{1}{AK_n} \cos^{-1} AV_n$$

The expression for ΔL is then obtained by making the substitution $V = V_{n+1}$ in L, or

$$L = L_n + \frac{1}{AK_n}(\cos^{-1} AV_n - \cos^{-1} AV) \tag{20}$$

so that

$$\Delta L = L_{n+1} - L_n = \frac{1}{AK_n} (\cos^{-1} AV_n - \cos^{-1} AV_{n+1}) \tag{21}$$

The only parameter yet to be described is y, or the vertical component of the length of the sound ray as it progresses through layer "n". The altitude y as a function of V is, of course, expressed by equation (2). Now the expression for y will be derived as a function of x. Using equations (8) and (14),

$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{V_y}{V_x} = \frac{V \sqrt{1 - \cos^2 \theta}}{V \cos \theta}$$

or,

$$\frac{dy}{dx} = \frac{\sqrt{1 - A^2V^2}}{AV}$$

Then substituting equation (4) for V,

$$\frac{dy}{dx} = \frac{\sqrt{1 - A^2(S_n + K_ny)^2}}{A(S_n + K_ny)}$$

or upon rearranging,

$$\frac{A(S_n + K_ny)\ dy}{\sqrt{1 - A^2(S_n + K_ny)^2}} = dx \tag{22}$$

Integrating equation (22),

$$x = C_4 - \frac{\sqrt{1 - A^2(S_n + K_ny)^2}}{AK_n} \tag{23}$$

Realizing that when $x = x_n$; $y = y_n$ or

$$S_n + K_ny_n = (V_n - K_ny_n) + K_ny_n = V_n$$

therefore,

$$C_4 = \frac{(1 - A^2V^2{}_n)^{1/2}}{AK_n} + x_n$$

or substituting in equation (23)

$$x = x_n + \frac{(1 - A^2V^2{}_n)^{1/2}}{AK_n} - \frac{(1 - A^2(S_n + K_ny)^2)^{1/2}}{AK_n} \tag{24}$$

Rearranging and squaring both sides of equation (23)

$$(x - C_4)^2 = \frac{1 - A^2(S_n + K_ny)^2}{A^2K_n{}^2}$$

or, upon further rearranging,

$$\frac{1}{A^2 K_n^2} = (x - C_4)^2 + (y + \frac{S_1}{K_n})^2 \qquad (25)$$

Equation (25) is the familiar representation of the algebraic expression for the path of a sound ray. It is obviously of the form

$$R^2 = (x - a)^2 + (y - b)^2$$

or the equation of a circle. Solving equation (24) for y,

$$y = - \frac{S_n}{K_n} + \frac{\sqrt{1 - \left[AK_n\ (x - x_n) - \sqrt{1 - A^2 V^2{}_n}\right]^2}}{AK_n} \qquad (26)$$

Thus, all unknown parameters are defined in terms of known parameters. Only the peak of the sound ray curve remains to be defined. First, it must be determined in which layer the ray peaks. Since S_n/K_n is the y displacement of the center of the circular arc from the origin or sound source and the absolute value of $\frac{1}{AK_n}$ is the radius, a ray peaks in layer "n" if

$$y_{n+1} + \frac{S_n}{K_n} \geq \left| \frac{1}{AK_n} \right| \qquad (27)$$

Thus, it is known in which layer a ray peaks. The last expression to be found is the altitude at which the peak occurs. At the peak, the angle the ray makes with the horizontal is zero degrees and from Snell's Law

$$A = \frac{\cos \theta}{V}$$

but at the peak $\theta = 0°$, and, therefore, the velocity at the peak, V_b, is

$$V_b = \frac{1}{A} \qquad (28)$$

Since the layer in which the peak occurs has been found from equation (27), then V_n is also known. By referring to equation (2), the altitude at the peak, y_b, can be calculated as

$$y_b = y_n + \frac{1}{K_n} (V_b - V_n)$$

or substituting from equation (28),

$$y_b = y_n + \frac{1 - AV_n}{AK_n} \tag{29}$$

Thus, the peak is fully described. One condition which is not described by the previous equations is when $K_n = 0$. When this condition occurs, the velocity remains constant throughout layer "n", and since Snell's Law still holds, the angle θ must also remain constant. Therefore, if

$$K_n = 0,\ V_n = V_{n+1} = V \text{ and}$$

$$x = x_n + \frac{AV_n (y - y_n)}{\sqrt{1 - A^2 V^2_n}} \tag{30}$$

$$L = L_n + \triangle L = L_n + \left(\frac{x - x_n}{AV_n} \right) \tag{31}$$

$$t = t_n + \frac{x - x_n}{AV^2_n} = t_n + \frac{\triangle L}{V_n}$$

The above equations have not been derived in this report since the ray path for $K_n = 0$ is a straight line throughout layer "n" and the relationships are, therefore, all linear functions.

SECTION IV. ANALYSIS OF SOUND RAY DATA FROM AD/ECS DIGITAL COMPUTER

The propagation of sound waves has been analyzed using the equations listed in Section III. These equations were then programmed for solution on the General Mills AD/ECS digital computer. Output of the AD/ECS, at the present time, has been analyzed and the results will be discussed in this section. Many interesting and important possibilities for further analysis have been the largest single contribution of the data received to date. This is especially true with regard to "destructive focusing", as defined by Warren W. Berning in his Ballistic Research Laboratories Report No. 675, "Investigation of the Propagation of Blast Waves Over

Relatively Large Distances and the Damaging Possibilities of Such Propagation". He defines "destructive focusing" as the phenomenon which occurs when two rays, traveling different paths, return to the ground at the same distance from the source and in the same amount of travel time. Constructive interference will occur and an irregular jump in peak overpressure will take place. More information about destructive focusing follows in this section.

In FIGURES 2 and 4, a few of the sound ray profile curves are plotted from the velocity of sound gradients shown in FIGURES 1 and 3. The sound profiles of FIGURE 2 correspond with the gradients in FIGURE 1, and those of FIGURE 4 correspond with the gradients shown in FIGURE 3. These figures show that in order for a positive velocity gradient to return sound rays to the earth, the maximum velocity acquired by the sound ray, due to this gradient, must be greater than the velocity of sound at any lower altitude and not just greater than the velocity of sound at the altitude of the source. The altitude of the sound source for these theoretical considerations is always zero feet. In addition, no consideration has been given to the effects caused by hilly or mountainous terrain. For the purposes of this investigation, the terrain is considered to be perfectly flat. This is another area in which further analysis is necessary.

Referring to FIGURE 5, the range of the returning sound rays in feet has been plotted versus the initial elevation angle of the sound ray in degrees. The dotted lines represent a family of curves with K_1 (the velocity of sound gradient throughout the first or lower layer of the atmosphere) equal to -0.001 feet per second per foot of altitude and Δh_1 (the height of the lower layer in feet) equal to 1,000 feet. The solid lines represent a family of curves in which K_1 is equal to -0.002 feet per second per foot of altitude and Δh_1 is equal to 1,000 feet. The lines labeled $\Delta h_2 = 1{,}000$ feet and $\Delta h_2 = 2{,}000$ feet are lines of constant thickness for the second or higher layer in which various positive gradients are present. These are typical curves of what might be called "negative-positive" gradient patterns. The curves seem to come from infinity in to a minimum value of the range and proceed to travel out again to a distance determined by the height of the second or positive layer. The property of these curves to double back on themselves in general shape of a parabola will be termed "focusing".

In FIGURE 5, it is readily apparent that as K_2 increases, the focusing becomes stronger and the range at which the focusing occurs moves in toward the source. As Δh_2 is increased, the width of the focusing zone is increased. For example, the curve $K_2 = +0.004$ and $\Delta h_1 = 1{,}000$ feet when $K_1 = -0.001$ has a minimum range of 70,500 feet. At $\Delta h_2 = 1{,}000$ feet, the range is 72,000 feet or a focusing zone of 1,500 feet along the ground. In this zone of 1,500 feet of range, all the sound rays having an initial elevation angle between 2.5° and 4.25° will impinge on earth's surface.

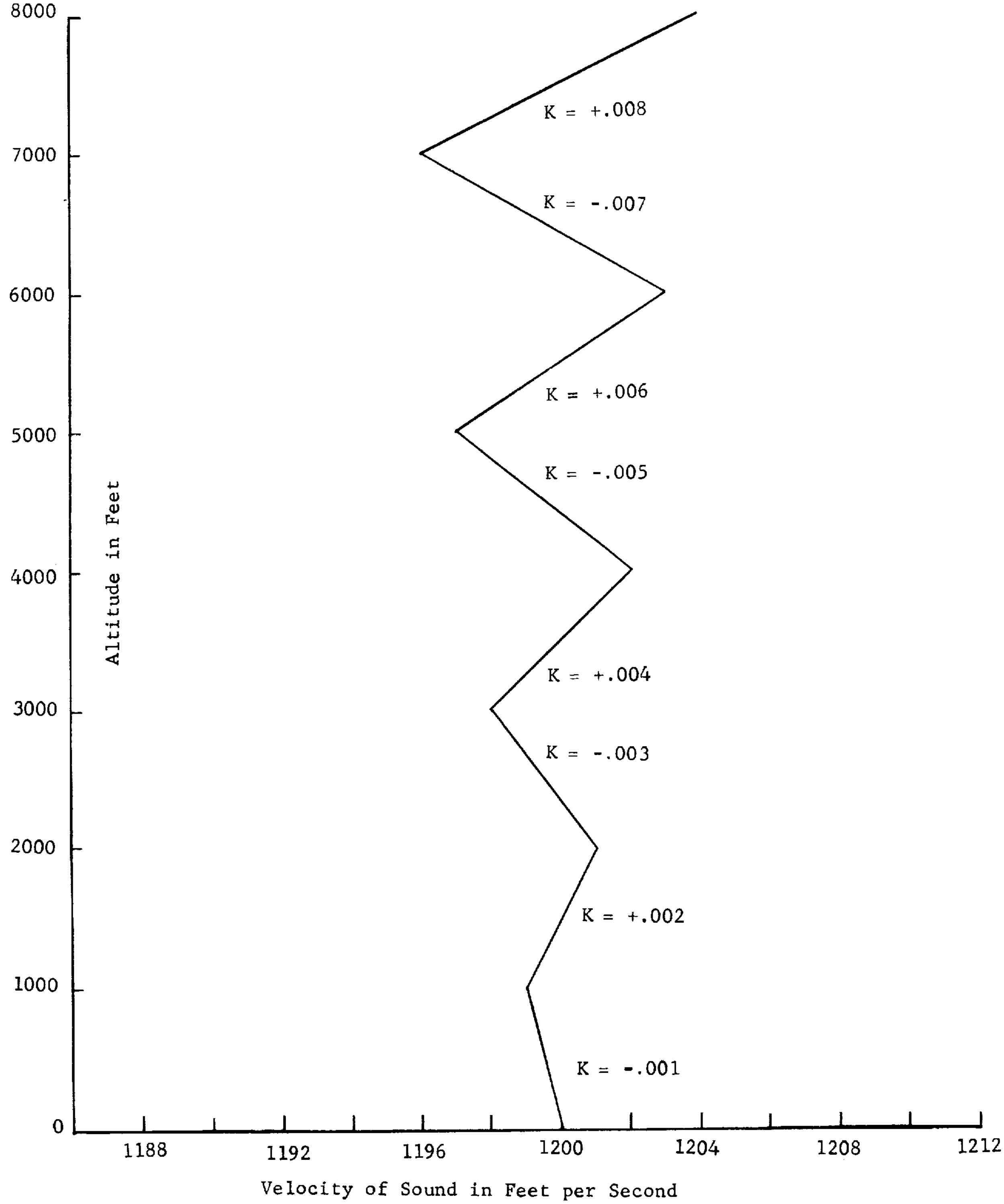


FIGURE 1. VELOCITY GRADIENT WITH 8 LAYERS

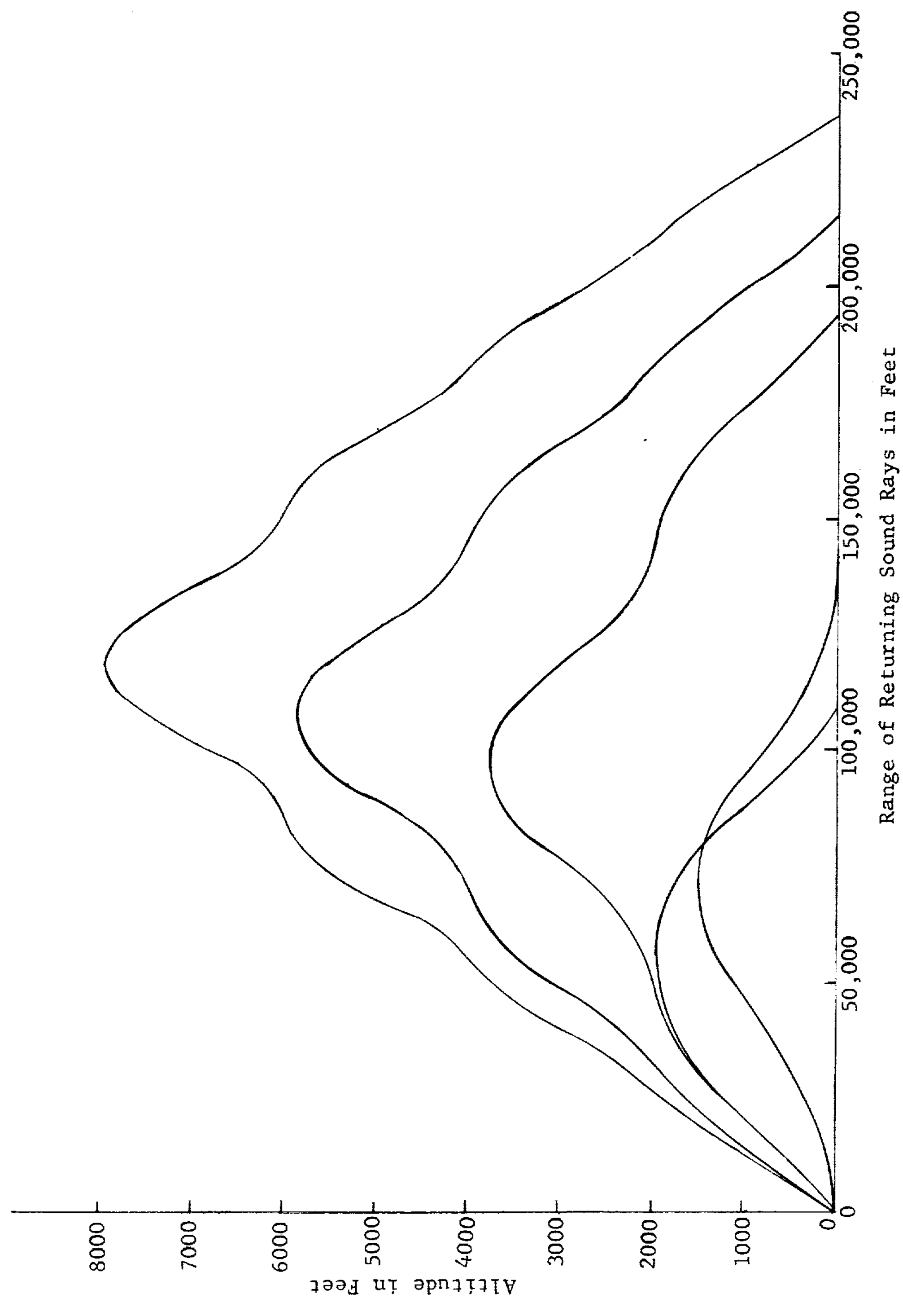


FIGURE 2. SOUND PROFILE OF FIGURE 1

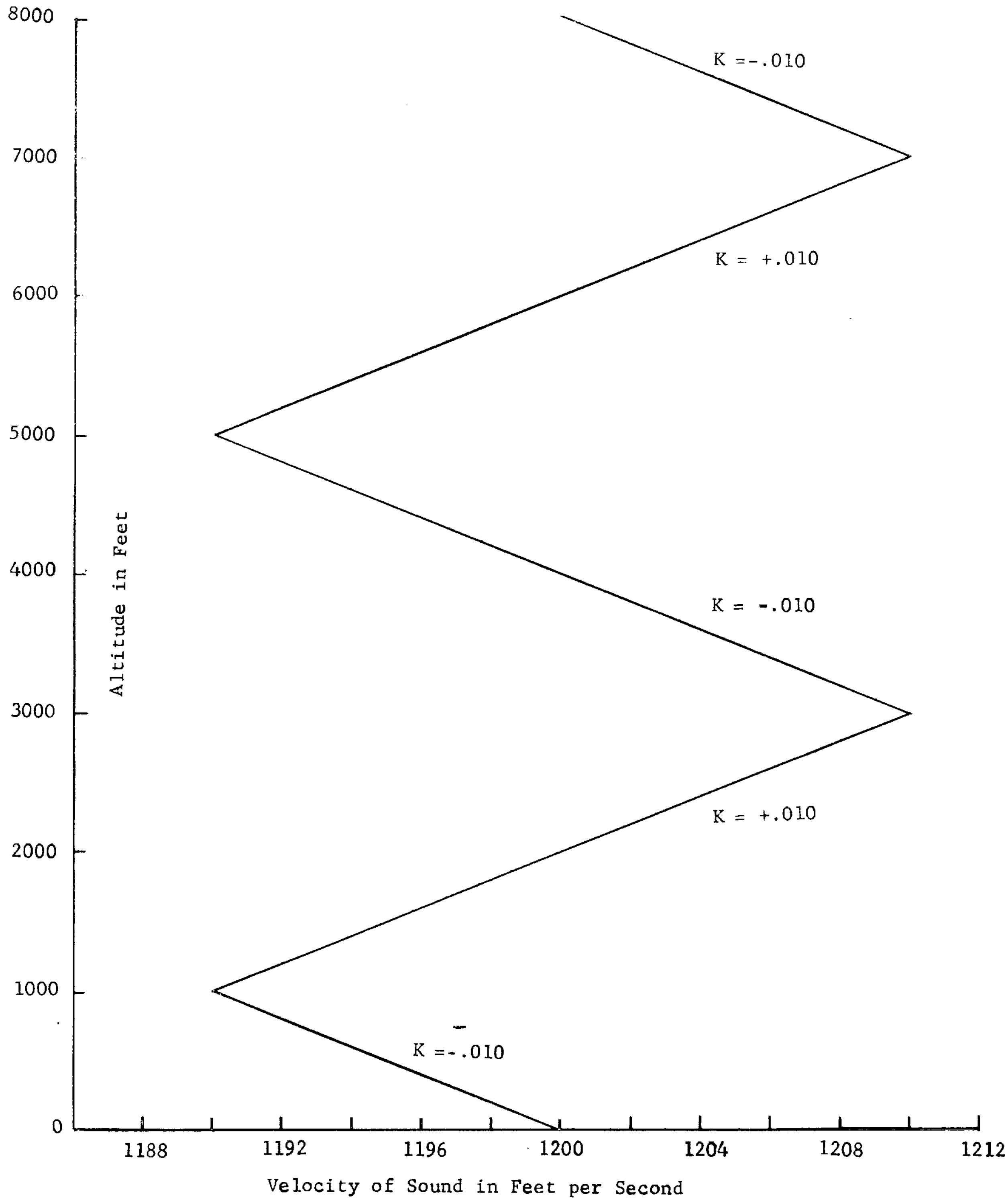


FIGURE 3. VELOCITY GRADIENT WITH 5 LAYERS

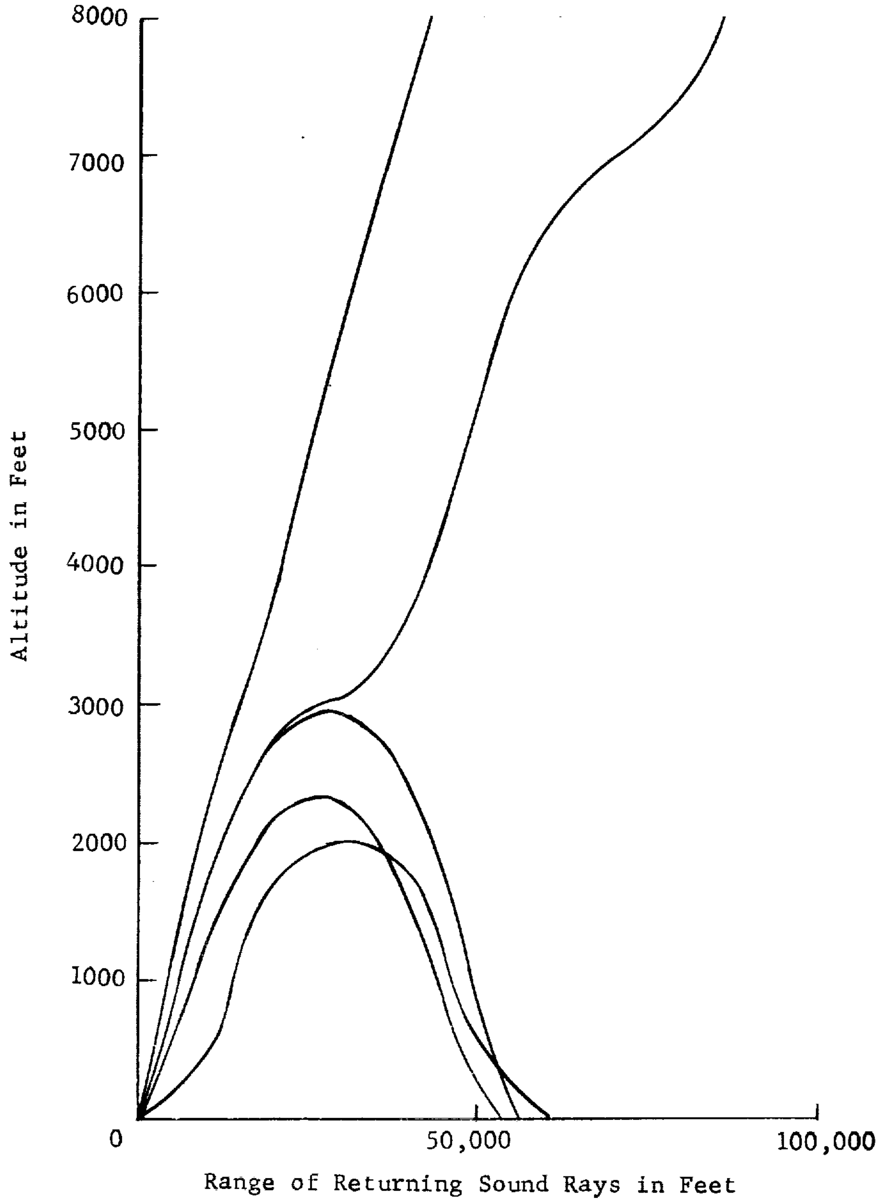


FIGURE 4. SOUND PROFILE RESULTING FROM FIGURE 3

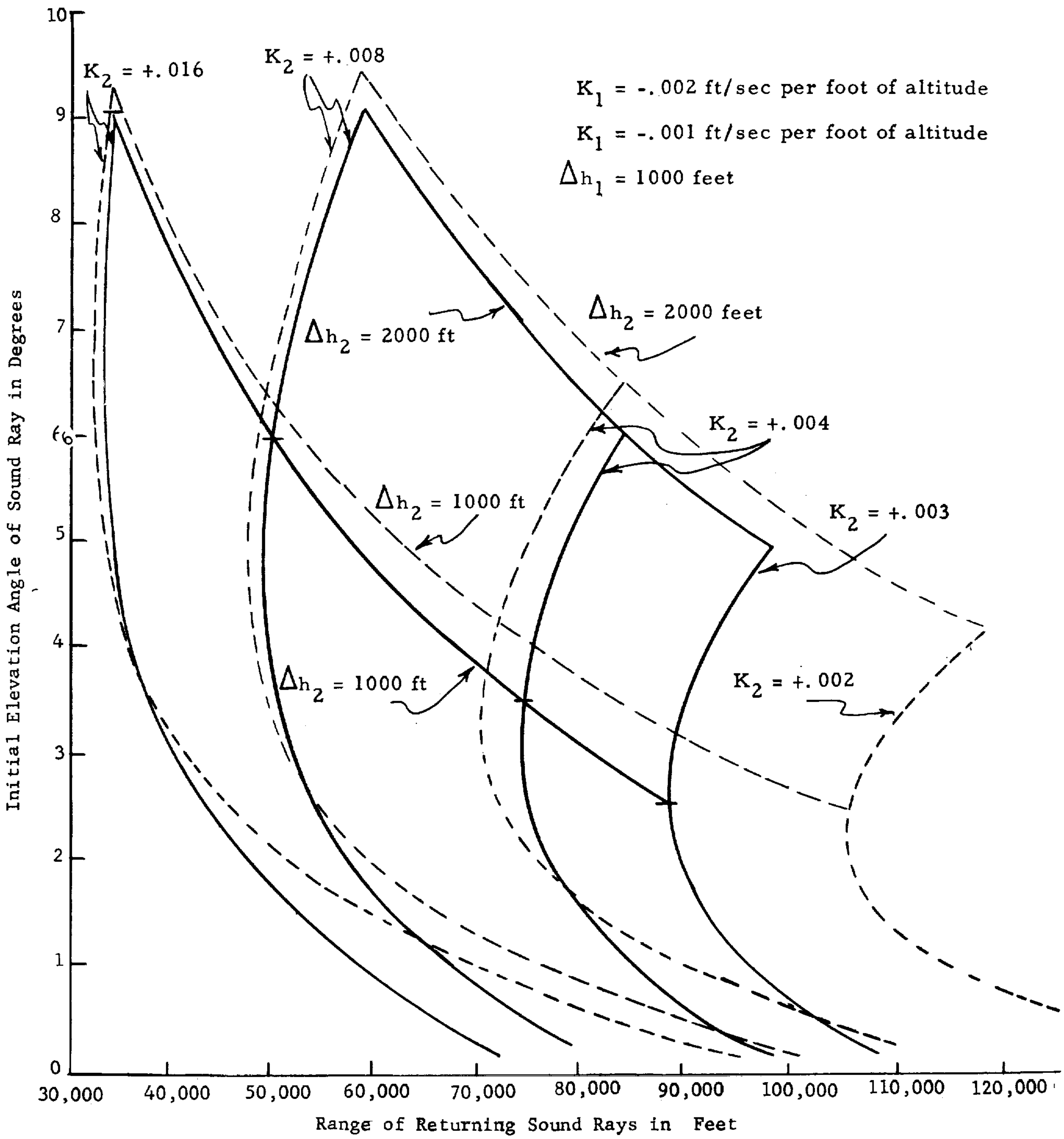


FIGURE 5. SOUND RAY IMPACT RANGE VS. ELEVATION ANGLE WITH NEGATIVE/POSITIVE GRADIENT

If Δh_2 is increased to 2,000 feet, the range is increased to 83,700 feet and the focusing zone becomes 13,700 feet. In this zone, all rays emanating from the source with an initial elevation angle between 1.25° and 6.25° will impinge on the earth. The focusing is not as strong throughout the total zone covered by Δh_2 = 2,000 feet, since 13,700 feet of range is covered by 5.00° of starting angle; whereas in the zone covered by Δh_2 = 1,000 feet, only 1,500 feet is blanketed by all the rays from 1.75° of starting angle. These figures are sharply contrasted by the lower portion of the curve K_2 = +0.004 and Δh_1 = 1,000 when K_1 = -0.001 where only 1° of starting angle covers the range from 83,700 feet to 110,000 feet or a zone of 26,300 feet. The strongest concentration of sound rays is obviously at the point of minimum range where the R versus θ curve begins to double back on itself. As K_2 increases in value, the focusing becomes stronger. Looking at the dotted curve, K_2 = +0.016 and Δh_1 = 1,000 feet when K_1 = -0.001, a range of only 1,500 feet is smothered by all the rays emanating from starting angles 4.625° through 9.375°, or 4.75° of initial elevation angle.

As the slope of the lower or upper portion of an R versus θ curve approaches zero or becomes more horizontal, the focusing concentration is reduced. For this reason, it is also seen from FIGURE 5, that if all other parameters remain constant and K_1 decreases or becomes more negative, the focusing concentration increases and the minimum range is moved farther away from the sound source. It is also seen that as K_2 is increased in value, the effect due to K_1 is reduced, except for the lower portion of curve. The minimum points move closer together and the isopleths of constant Δh_2 trend to converge.

FIGURE 6 demonstrates more clearly, the effect due to K_1 when K_2, Δh_1, and Δh_2 are held constant. As K_1 decreases, the curve approaches a vertical line which would be the most devastating type of focusing since all sound rays returning to the earth would strike at the same place on the surface. The movement of the minimum range, as K_1 varies, is also demonstrated very clearly in FIGURE 6. As K_1 becomes more negative in value, the minimum point increases.

FIGURE 7 refers to a "positive-positive" type of velocity gradient. The value of K_1 for this plot is +0.001 feet per second per foot of altitude. Increasing Δh_1 has an overall effect of increasing both the focusing concentration and the range at which the focusing zone occurs. As in the case of the "negative-positive" gradients, increasing K_2 causes an increase in the concentration of the focus and reduces the range at which the focusing occurs. For the "positive-positive" gradients, it is also seen that the effects due to Δh_1 are decreasing as K_2 increases. As K_1 becomes more positive, the slope of the straight line increases and the minimum range is moved closer to the sound source.

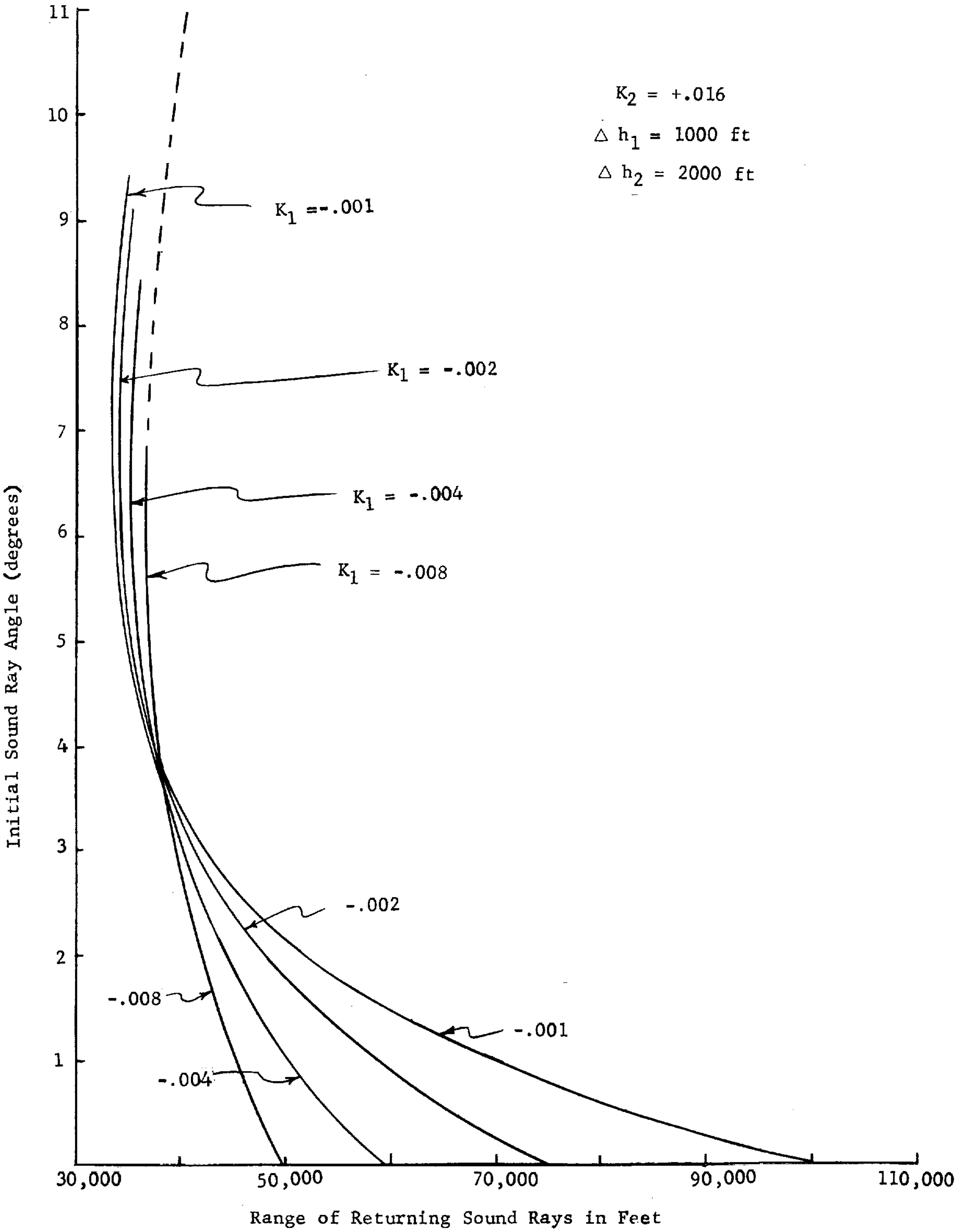


FIGURE 6. REPLOT OF FIGURE 5 WITH VARIABLE FIRST LAYER.

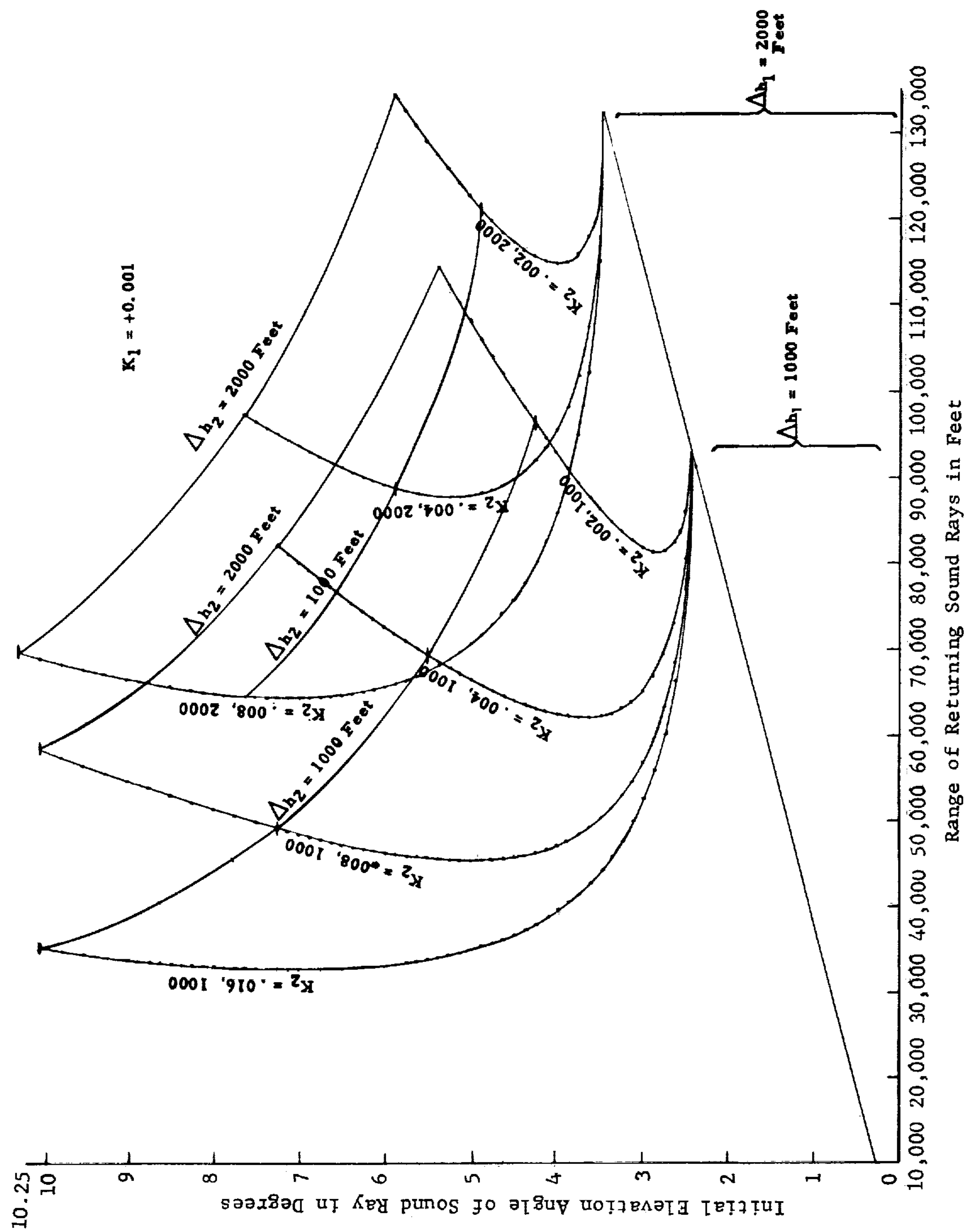


FIGURE 7. SOUND RAY IMPACT RANGE VS. ELEVATION ANGLE WITH POSITIVE-POSITIVE GRADIENT

At this point, the subject of "destructive focusing" will be discussed further. FIGURE 8 is a plot of the time required for a sound ray to return to the earth versus the range of the returning sound ray. It is readily apparent that range,is for all practical purposes, a linear function of the time and that the time is only a function of the velocity of sound at the source (Ref. 2). The time shows a variation in the fourth and fifth significant digit or hundredths of a second. Consequently, any ray having an initial velocity of 1,100 feet per second and returning at a range of 60,000 feet will take 52.3 seconds of travel time irrespective of its path. This tends to indicate that any focusing of the sound rays is "destructive focusing" as described by Warren W. Berning. Since the sound source, in this case, is active for a period of from 1.5 to 2 minutes, it appears that further analysis of this phenomenon is necessary to determine the effects of the high energy release of the source on the initial sound velocity throughout the firing time and other such related problems.

A series of computer runs were made with $K_1 = 0.001$ and $\Delta h_2 = 1{,}000$ feet. The velocity gradient in the second layer, K_2, was then varied for different values of Δh_1. Results are plotted in FIGURE 9 for Δh_1 equal to 1,000, 2,000, 3,000,and 4,000 feet. Since Huntsville, Alabama is located at a distance of roughly 60,000 to 70,000 feet from the source, a change in the velocity of sound of 20 feet per second (or $K_2 = +0.020$). from 4,000 to 5,000 feet is required to cause the sound rays to return to 70,000 feet, or the outer edge of Huntsville. A change in the velocity of sound of 20 feet per second during daytime, over 1,000 feet of altitude, is extremely rare and as the altitude increases it becomes even less probable. The evidence presented here is not conclusive because there is no variation of K_1, and the effect of this variation on the lines of constant Δh_1. However, it appears that measuring atmospheric conditions more accurately throughout the first 5,000 feet of altitude is much to be preferred over less accurate measurements up to 10,000 feet. In fact, it is likely that further analysis based on past meteorological data of Huntsville and the surrounding area will show that measurements above 5,000 feet are unnecessary.

FIGURE 10 shows the velocity gradients used to compute the data plotted in FIGURE 11. At the present time, the value of the velocity gradient is calculated to the third decimal place, indicating an error in any K value of ±0.0005 feet per second, per foot of altitude. Assuming an accuracy of five decimal places in K_1 and K_2, the middle line in FIGURE 11 was computed. The parameters for what will be termed the "actual" curve are $K_1 = +0.00000$ feet per second, per foot of altitude; $K_2 = +0.00400$ feet per second, per foot of altitude; $\Delta h_1 = 1{,}000$ feet; and $\Delta h_2 = 1{,}000$ feet. Then using the present accuracy of K (while holding Δh constant) and the worst possible combinations of the present error in K, the curves on the extreme left and right in FIGURE 11 were computed.

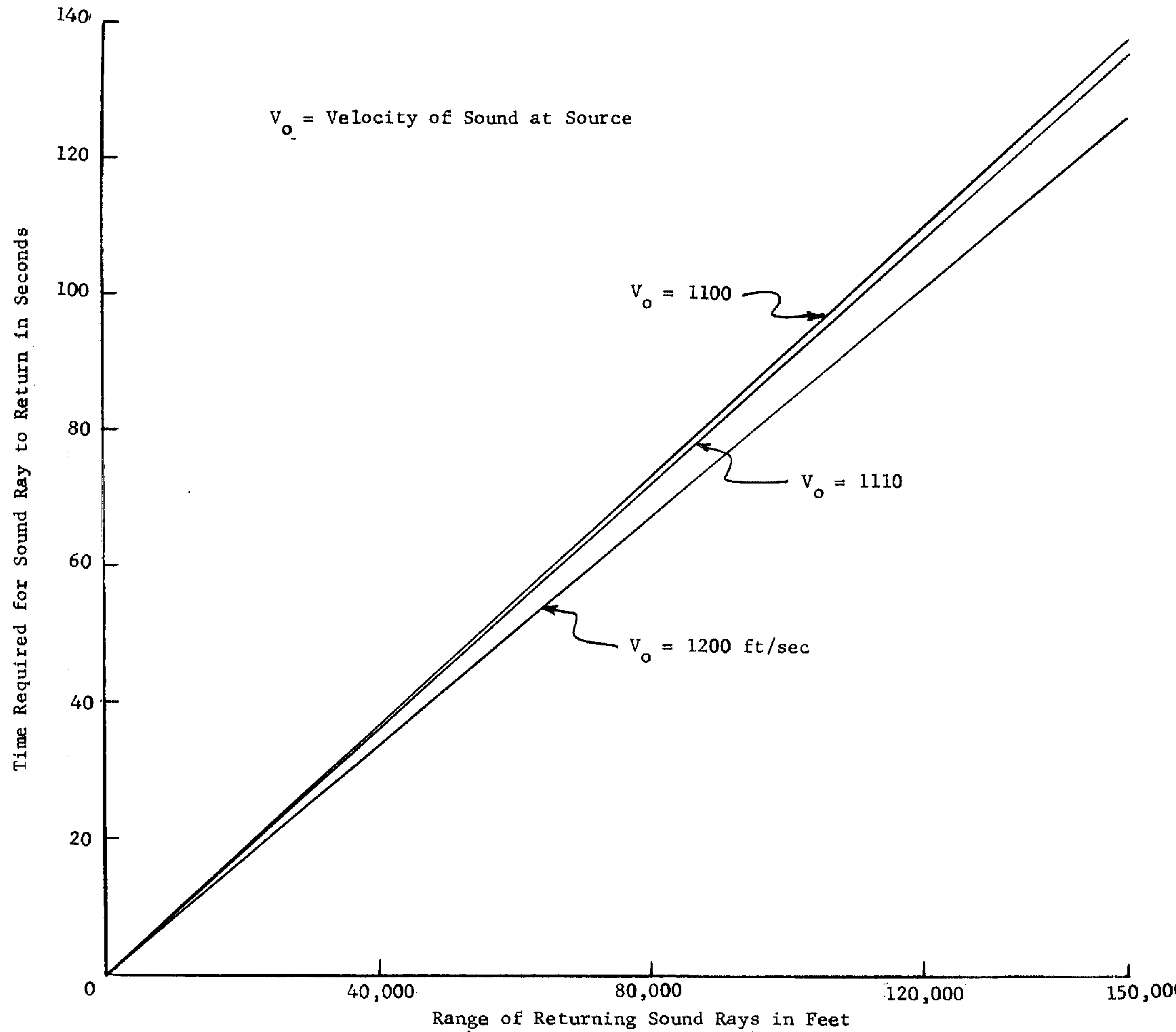


FIGURE 8. TIME OF TRAVEL VS. IMPACT RANGE

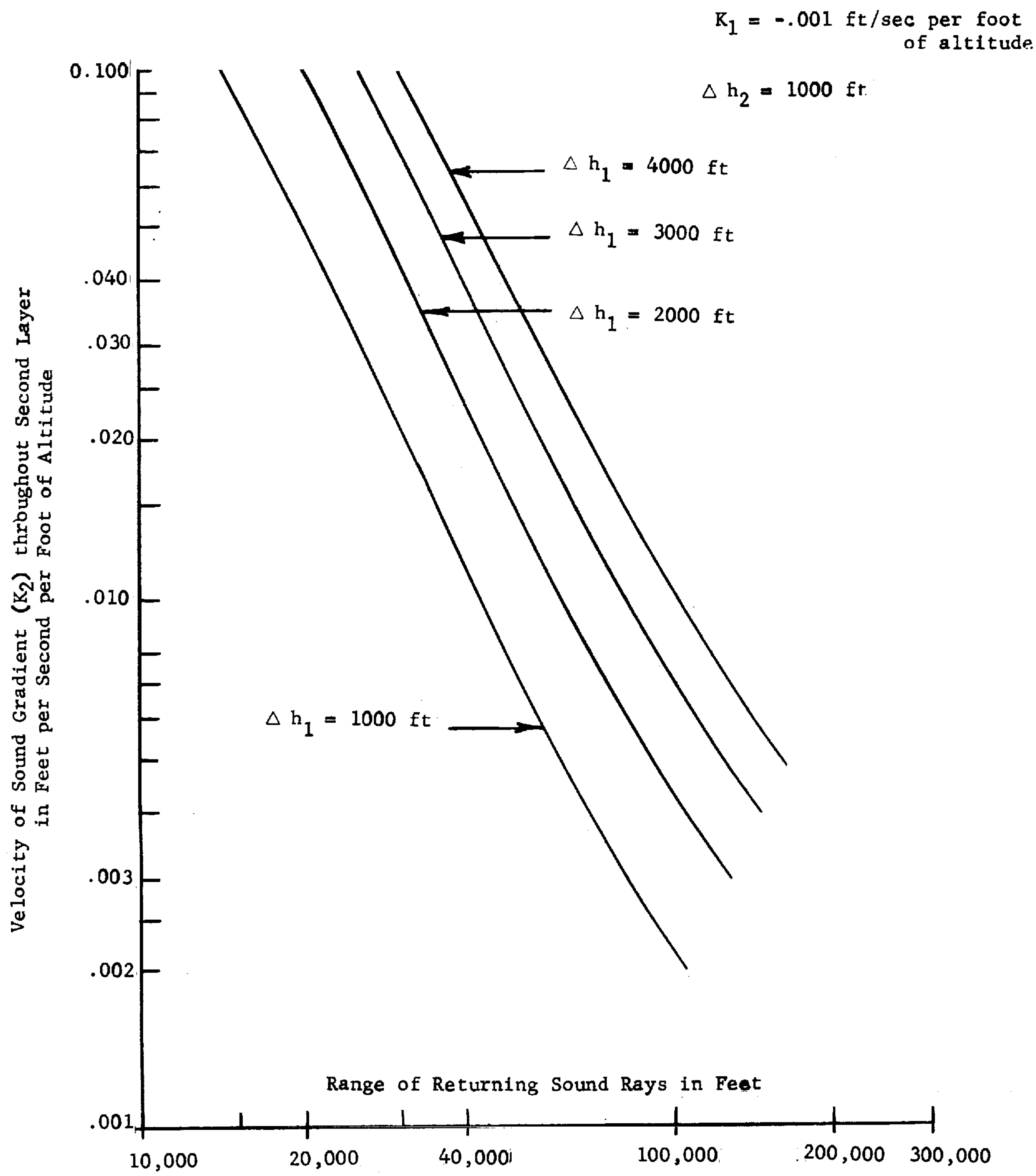


FIGURE 9. RANGE OF SOUND IMPACT WITH CONSTANT FIRST LAYER GRADIENT AND VARIABLE SECOND LAYER GRADIENT

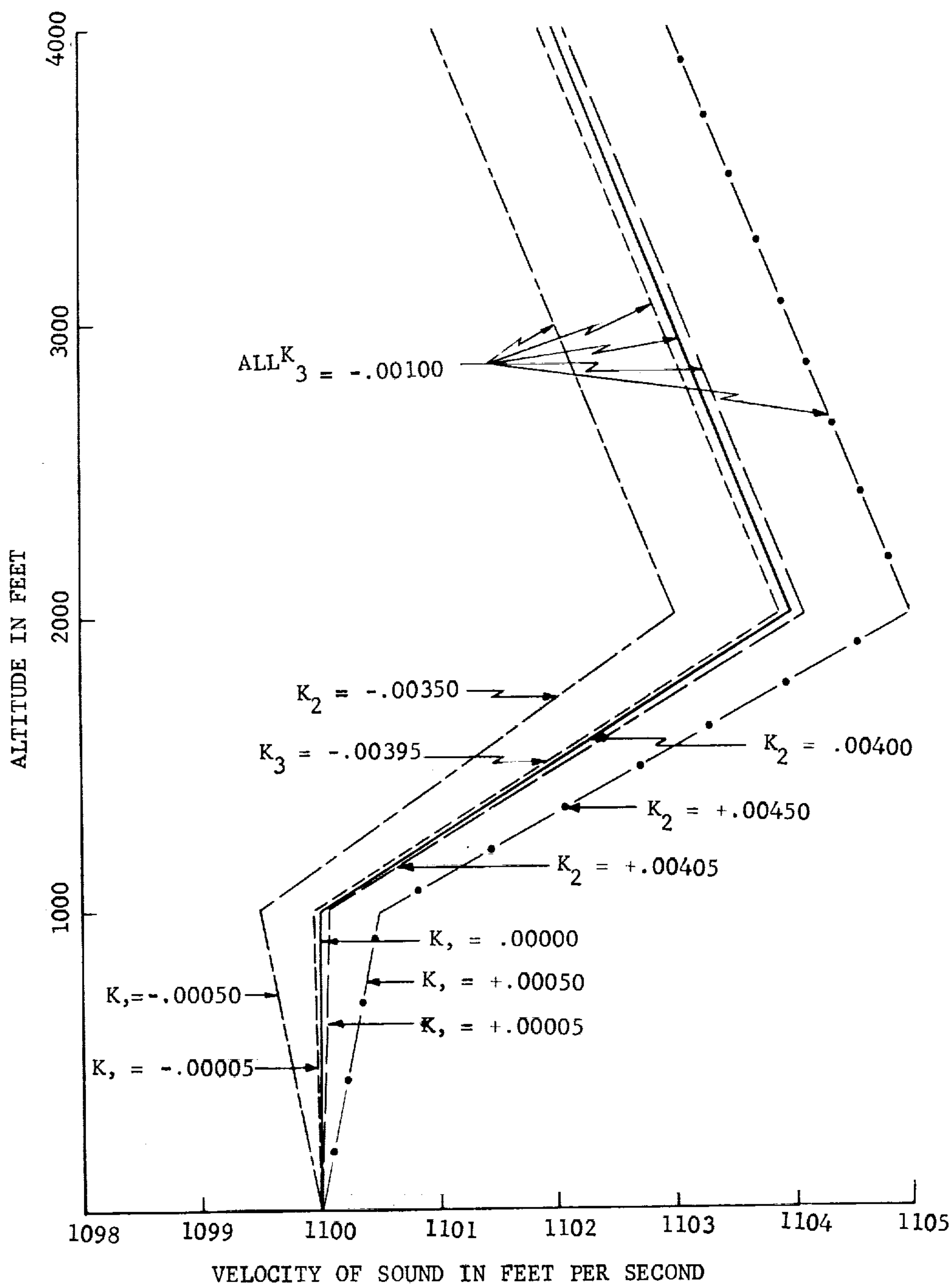


FIGURE 10. VELOCITY GRADIENT

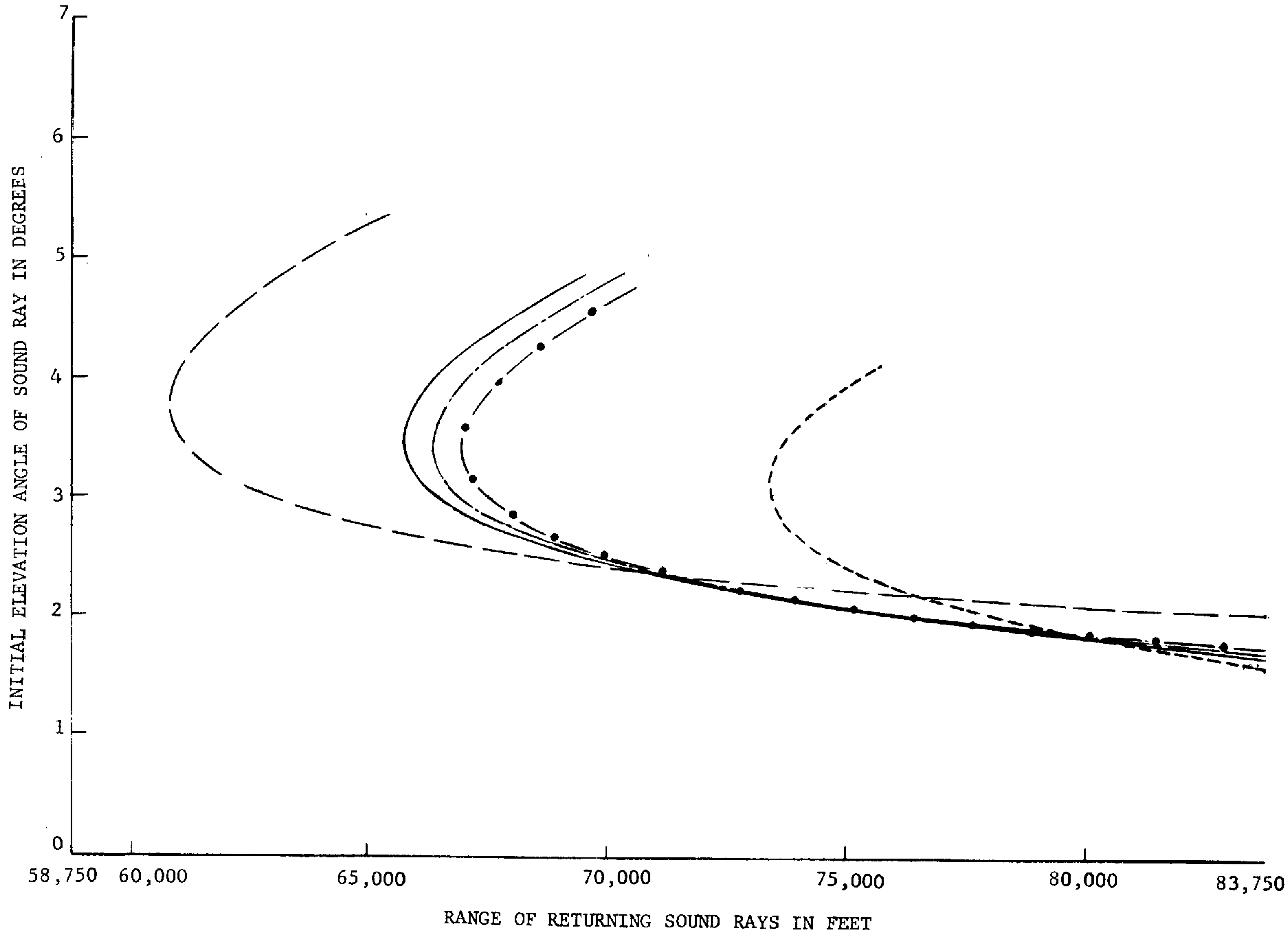


FIGURE 11. VARIATIONS IN IMPACT RANGE DUE TO VELOCITY GRADIENT ERRORS

The values of the velocity gradients for the curve on the extreme left are $K_1 = +0.0005$ and $K_2 = +0.0045$, and for the curve on the extreme right, $K_1 = -0.0005$ and $K_2 = +0.0035$. For the particular values of the "actual" K_1 and K_2 used here, the displacement of the minimum point, when using the implied error, is roughly ±7,000 feet.

If the accuracy of K could be increased to one more significant figure or four decimal places, the error would be reduced to ±0.00005 feet per second, per foot of altitude. The two curves on the immediate right and left of the "actual" curve represent the worst possible combinations of an error in the fifth decimal place. The curve on the immediate left has gradients of $K_1 = +0.00005$ and $K_2 = +0.00405$, and the curve on the immediate right has gradients of $K_1 = -0.00005$ and $K_2 = +0.00395$. Displacement of the minimum range for an implied error in the fifth decimal place is approximately ± 675 feet. FIGURE 11 shows that the accuracy of the sound field is approximately directly proportional to the accuracy of the instruments measuring the meteorological data.

The next problem considered was one of curve fitting. Since the idea of velocity gradients is nothing more than an attempt to fit the curve which exists in nature, smaller increments of altitude will undoubtedly fit the curve better and make the sound field computations more reliable. The term "reliable" is used rather than "accurate" because smaller increments of altitude will pick up irregularities in the curve which larger increments will never see.

The problem of accuracy was investigated by assuming the existence of a sine curve for the velocity gradient in nature. The increments of Δh were then reduced from 1,000 feet to 500 feet to 250 feet and finally to 125 feet. The velocity gradients are shown in FIGURES 12, 13, 14, and 15, and the range versus initial elevation angle plots computed from these gradients are shown in FIGURE 16. The total variation in the minimum range between the 1,000-foot increment curve and the actual sine curve (represented as a "hairy" line) is roughly 10,000 feet; whereas, the difference between the 250-foot increment curve and the actual curve is 400 feet.

One of the interesting effects brought out by the curves in FIGURE 16 is a great variation in the upper part of the sound field, caused by a positive gradient followed by a less positive gradient. This should, in part, point out the tremendous effect that can be caused by a minor irregularity developing over a few hundred feet of altitude.

FIGURES 17, 19, 21, and 23 are the velocity gradients for FIGURES 18, 20, 22, and 24 respectively. The gradients were calculated from the data listed in Table I (Page 50). These data were taken from page 27 of the BRL Report No. 1118, "Forecasting the Focus of Air Blasts Due to Metoro logical Conditions in the Lower Atmosphere".

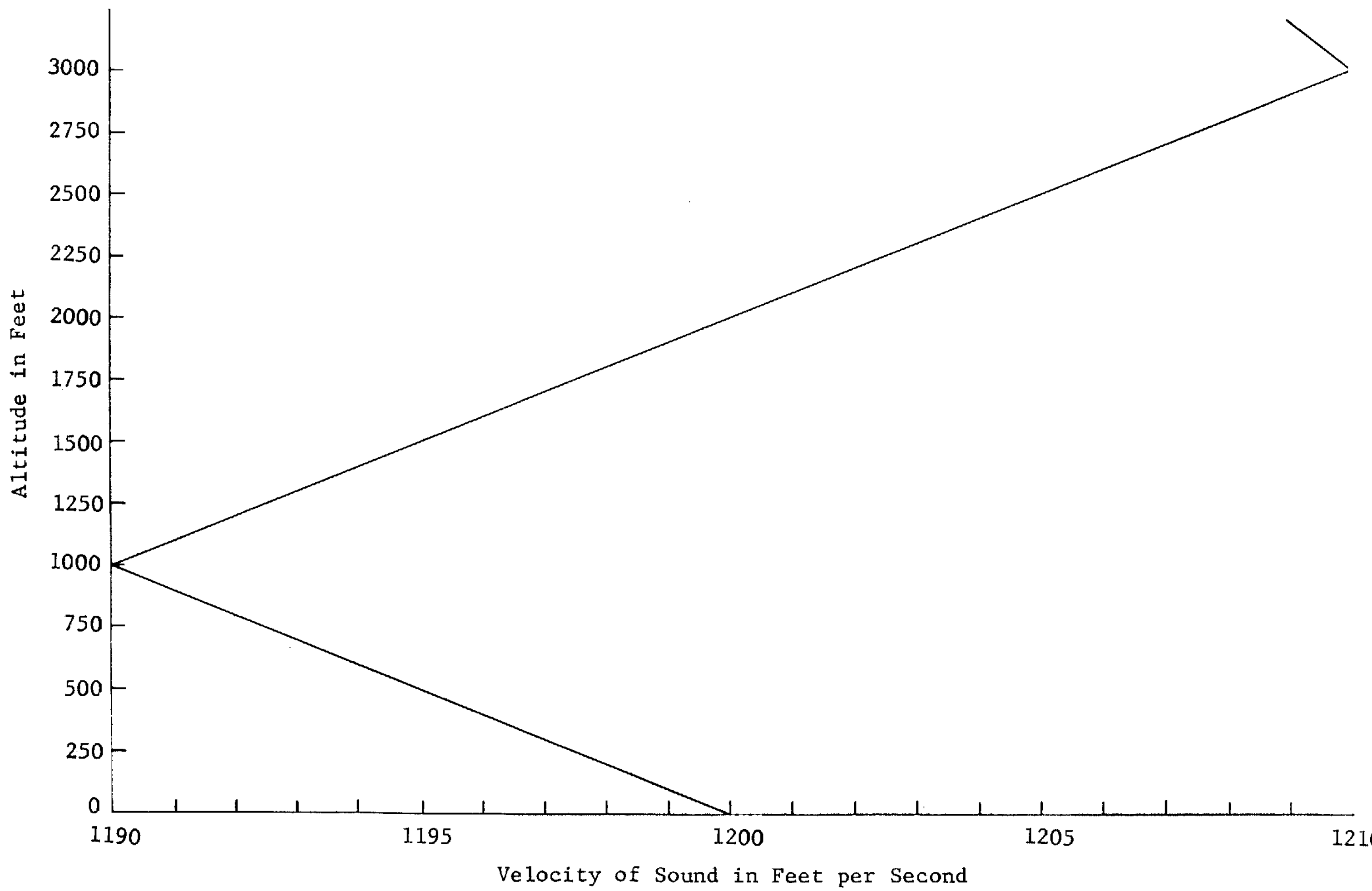


FIGURE 12. VELOCITY GRADIENT TO FIT SINE CURVE WITH 1000 FEET ALTITUDE INCREMENTS.

FIGURE 13. VELOCITY GRADIENT TO FIT SINE CURVE WITH 500-FOOT ALTITUDE INCREMENTS

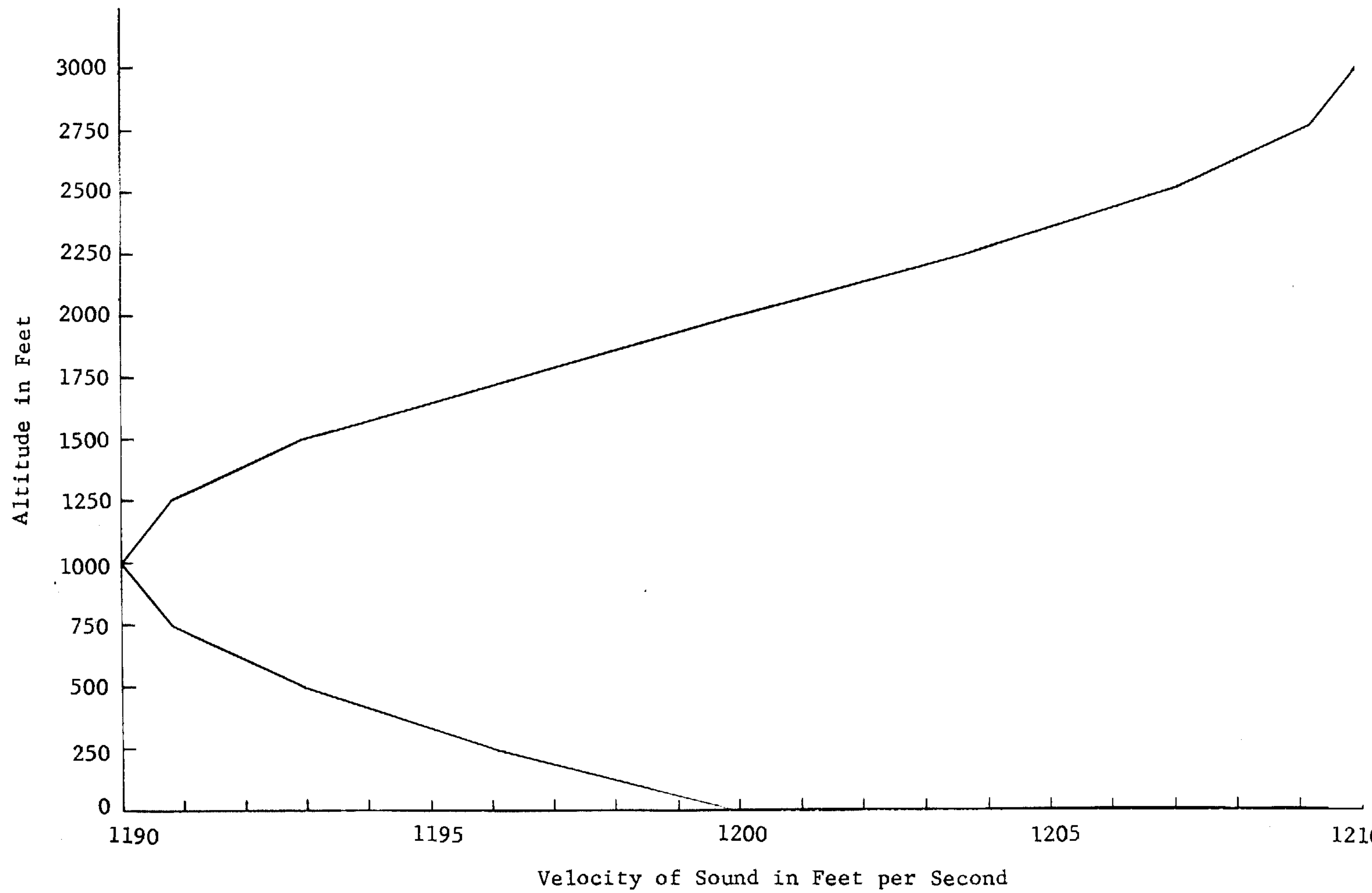


FIGURE 14. VELOCITY GRADIENT TO FIT SINE CURVE WITH 250-FOOT ALTITUDE INCREMENTS.

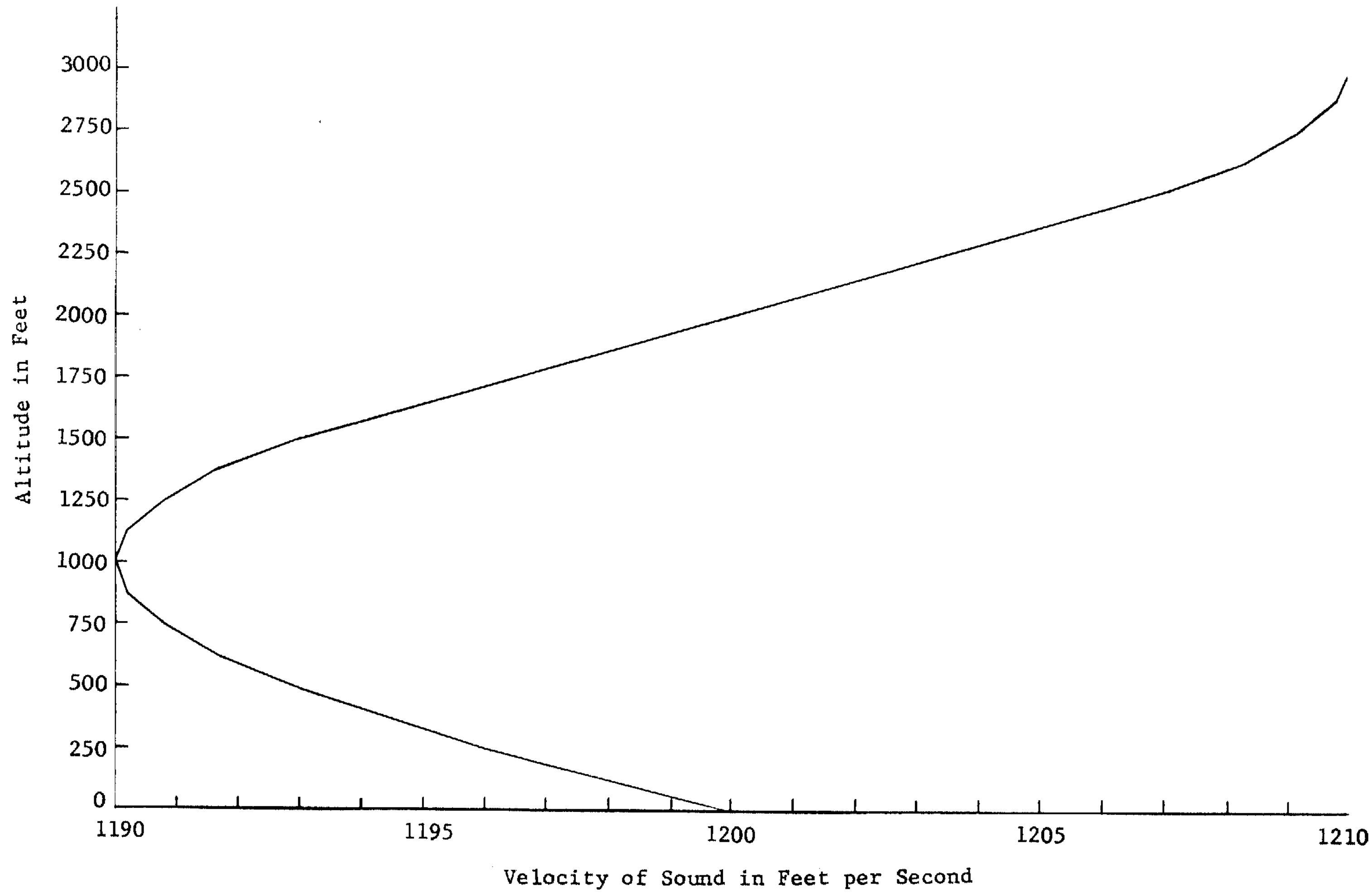


FIGURE 15. VELOCITY GRADIENT TO FIT SINE CURVE WITH 125-FOOT ALTITUDE INCREMENTS.

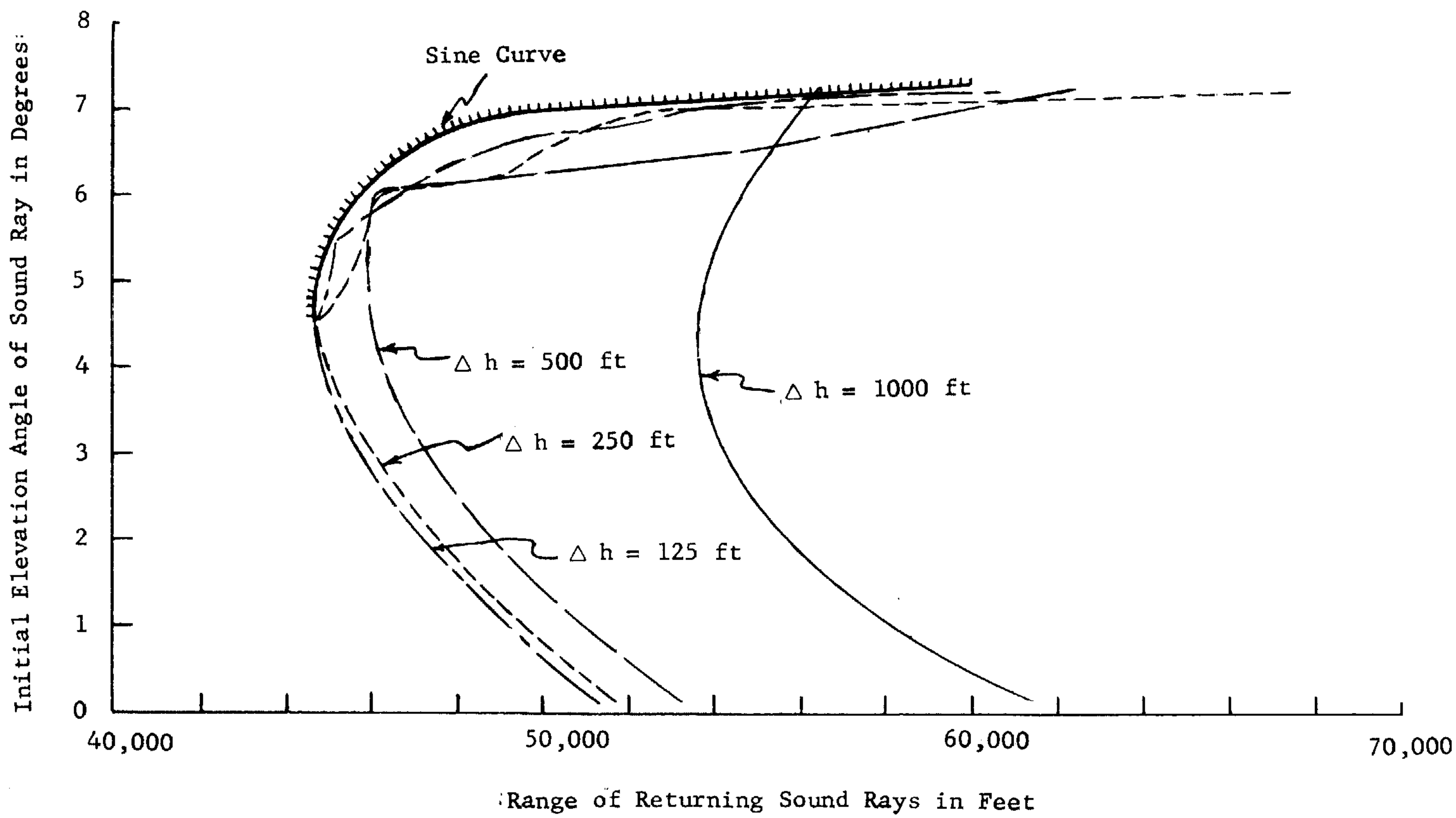


FIGURE 16. VARIATIONS IN IMPACT RANGE DUE TO SIZE OF ALTITUDE SAMPLING INSTRUMENT

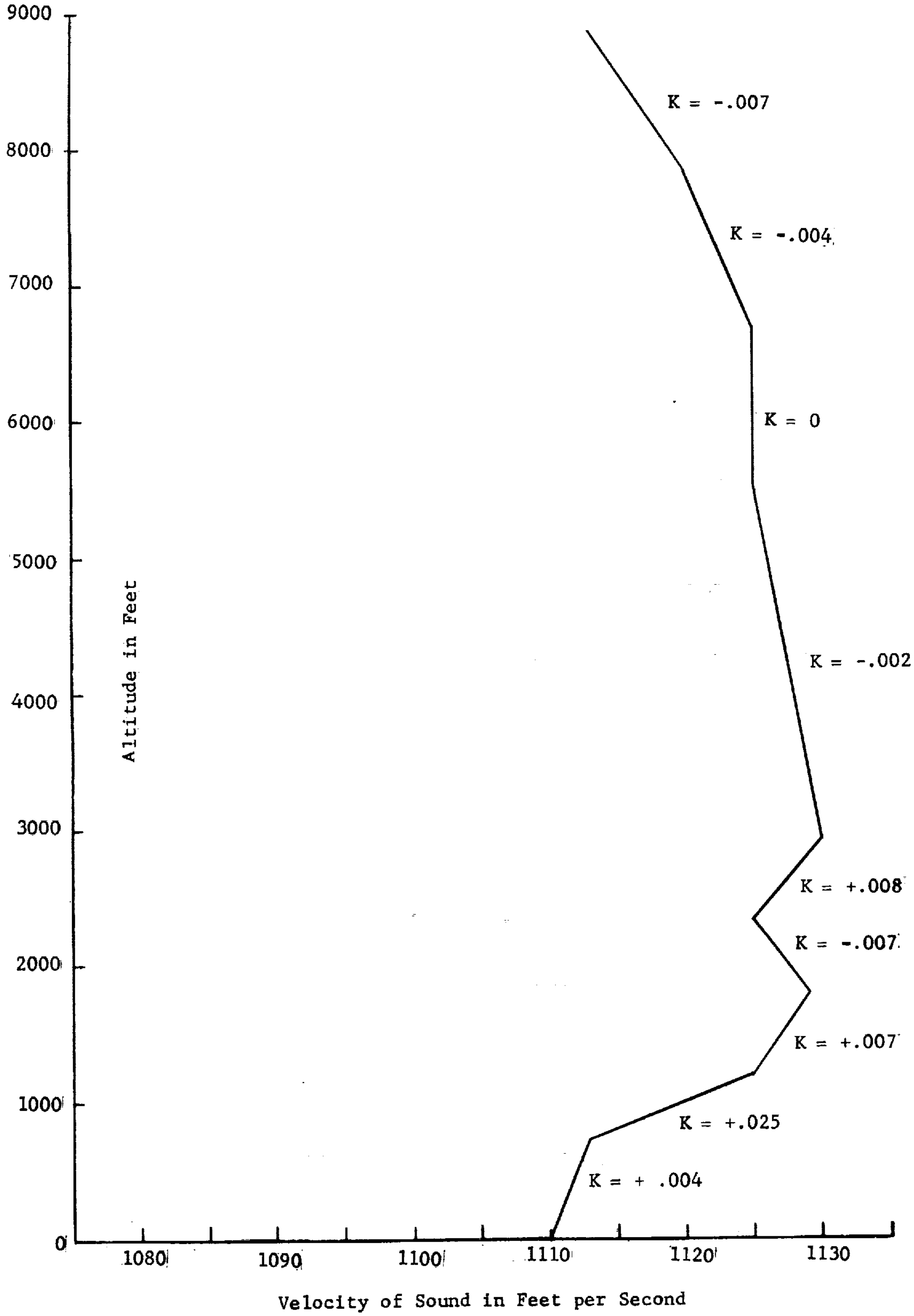


FIGURE 17. VELOCITY GRADIENT FOR 0° AZIMUTH

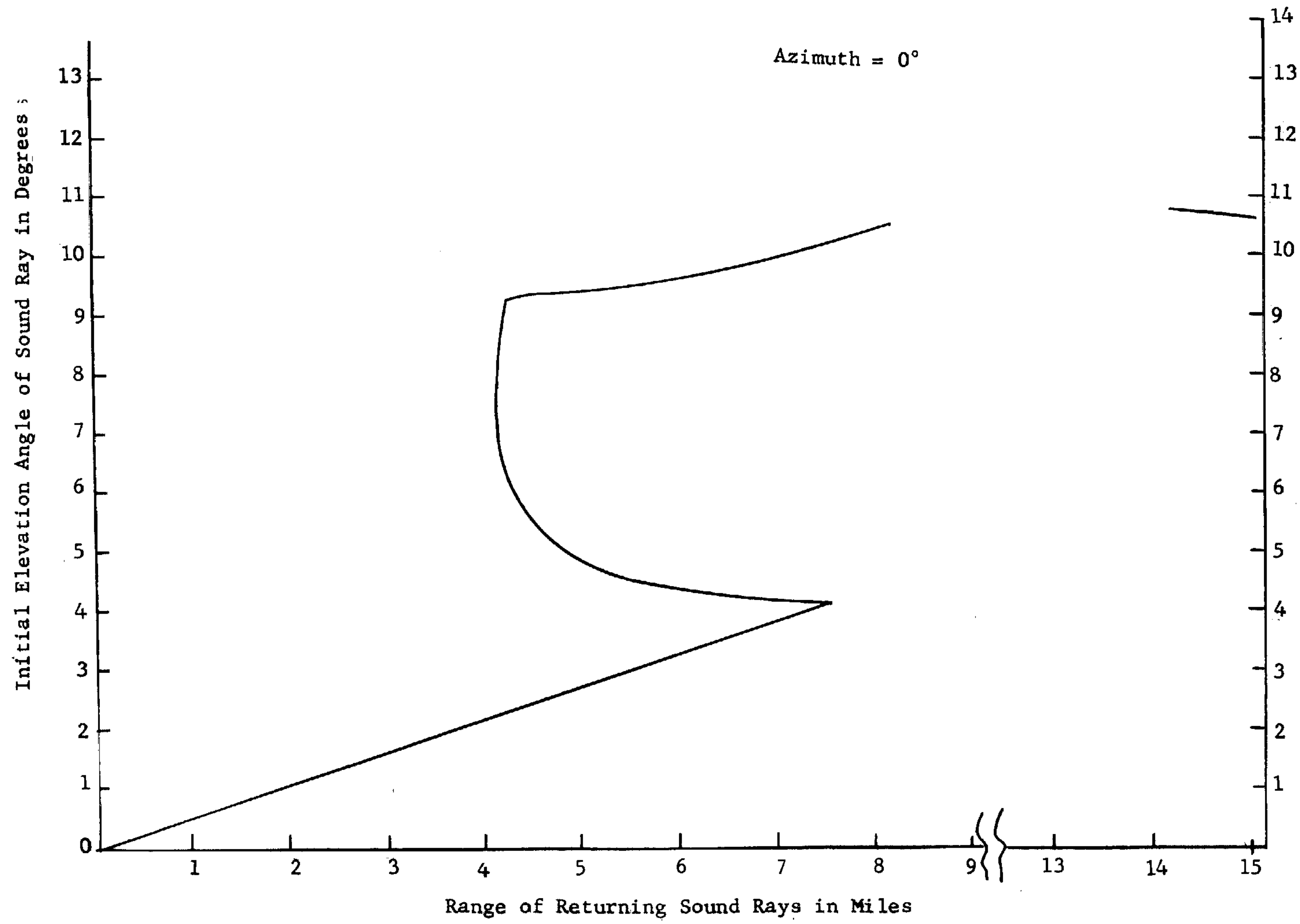


FIGURE 18. IMPACT RANGE FOR 0° AZIMUTH

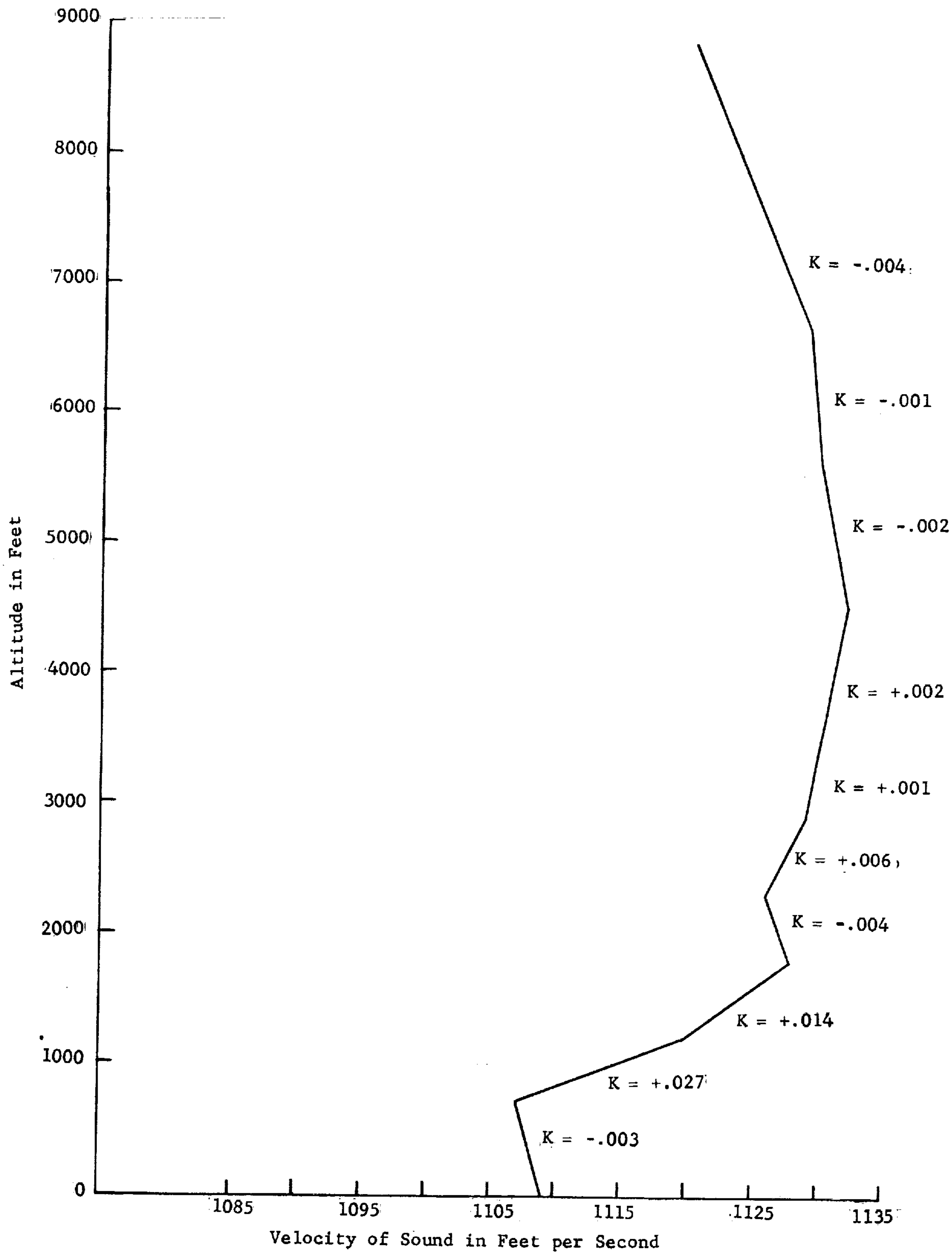


FIGURE 19. VELOCITY GRADIENT FOR 30° AZIMUTH

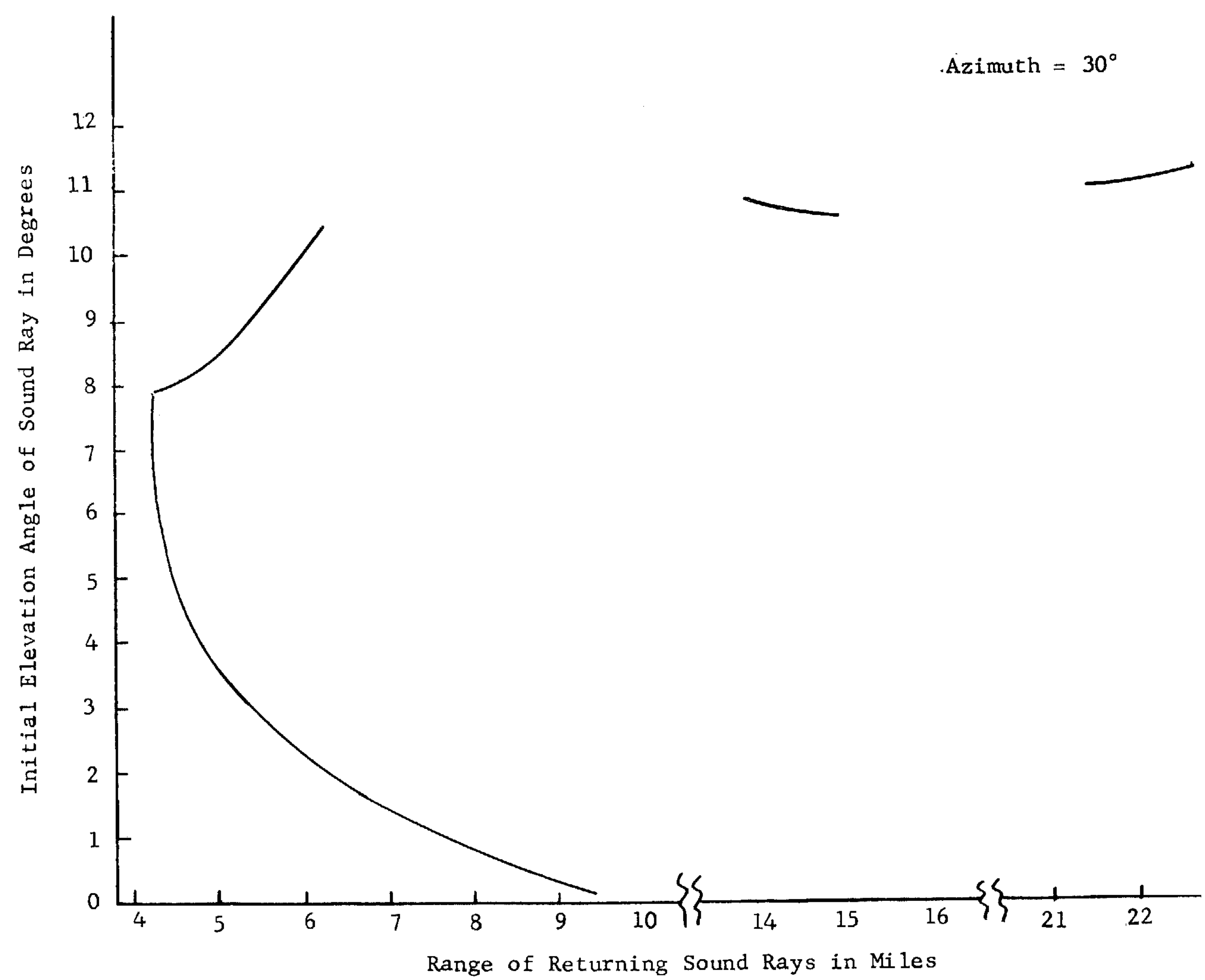


FIGURE 20. IMPACT RANGE FOR 30° AZIMUTH

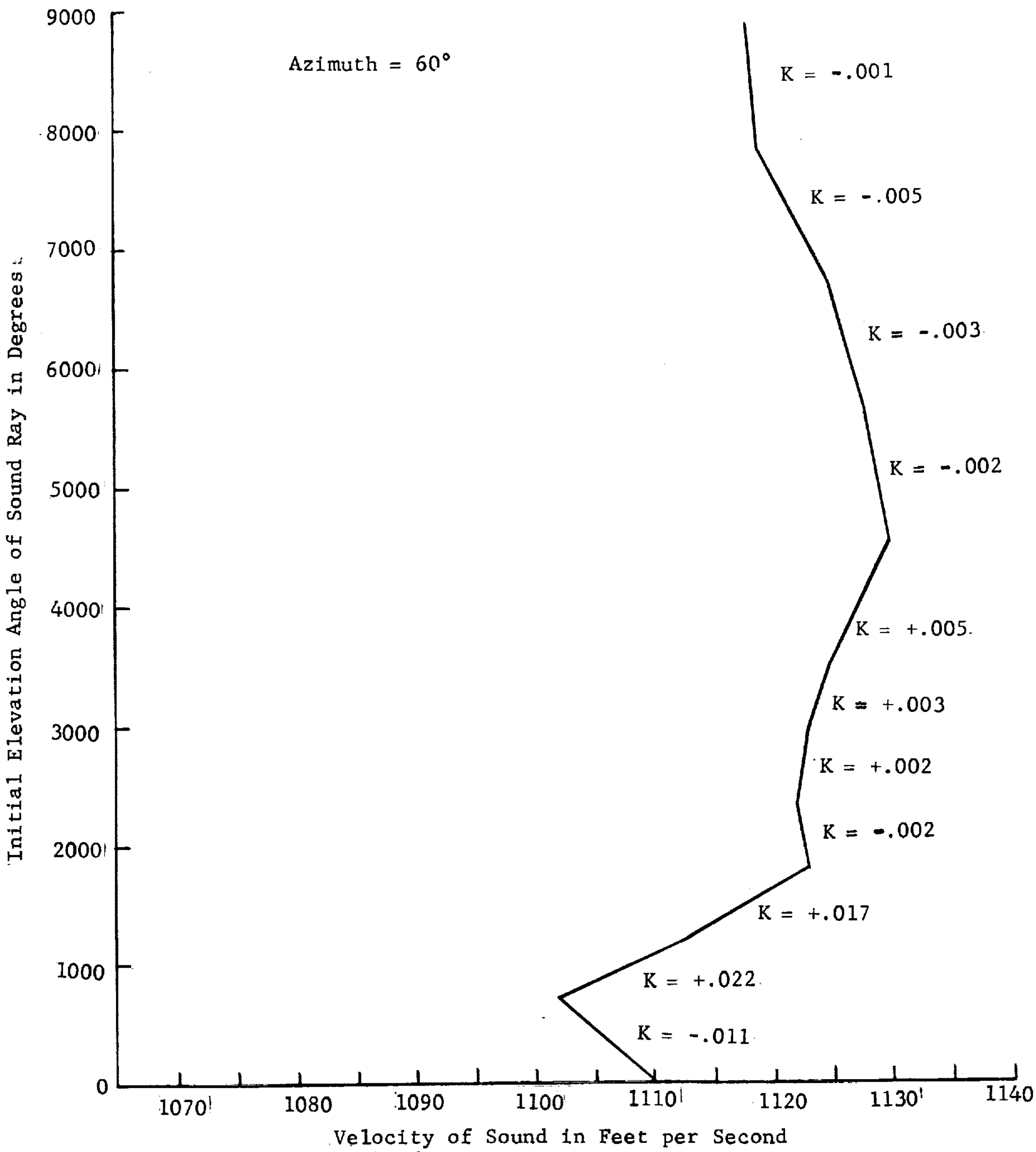


FIGURE 21. VELOCITY GRADIENT FOR 60° AZIMUTH

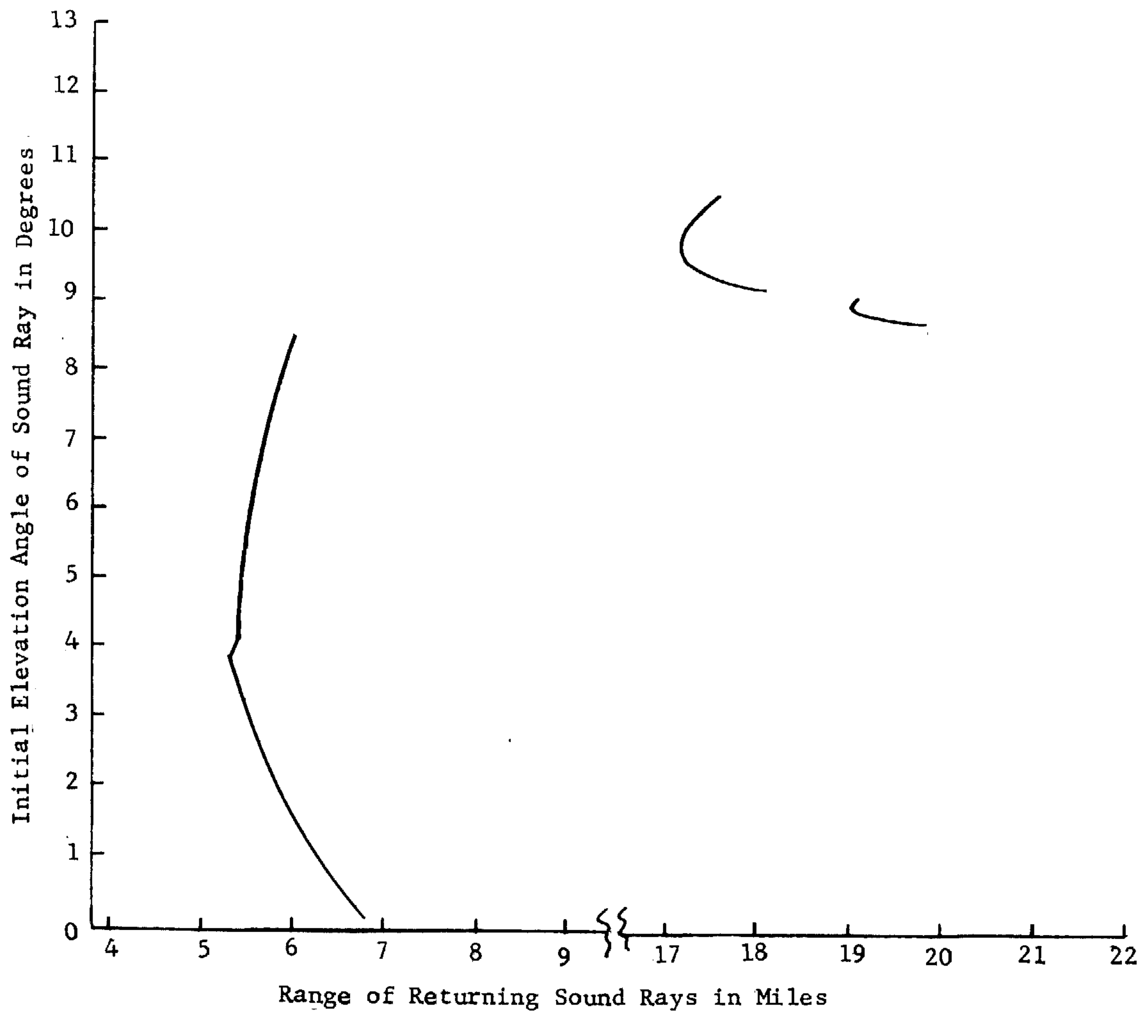


FIGURE 22. IMPACT RANGE FOR 60° AZIMUTH

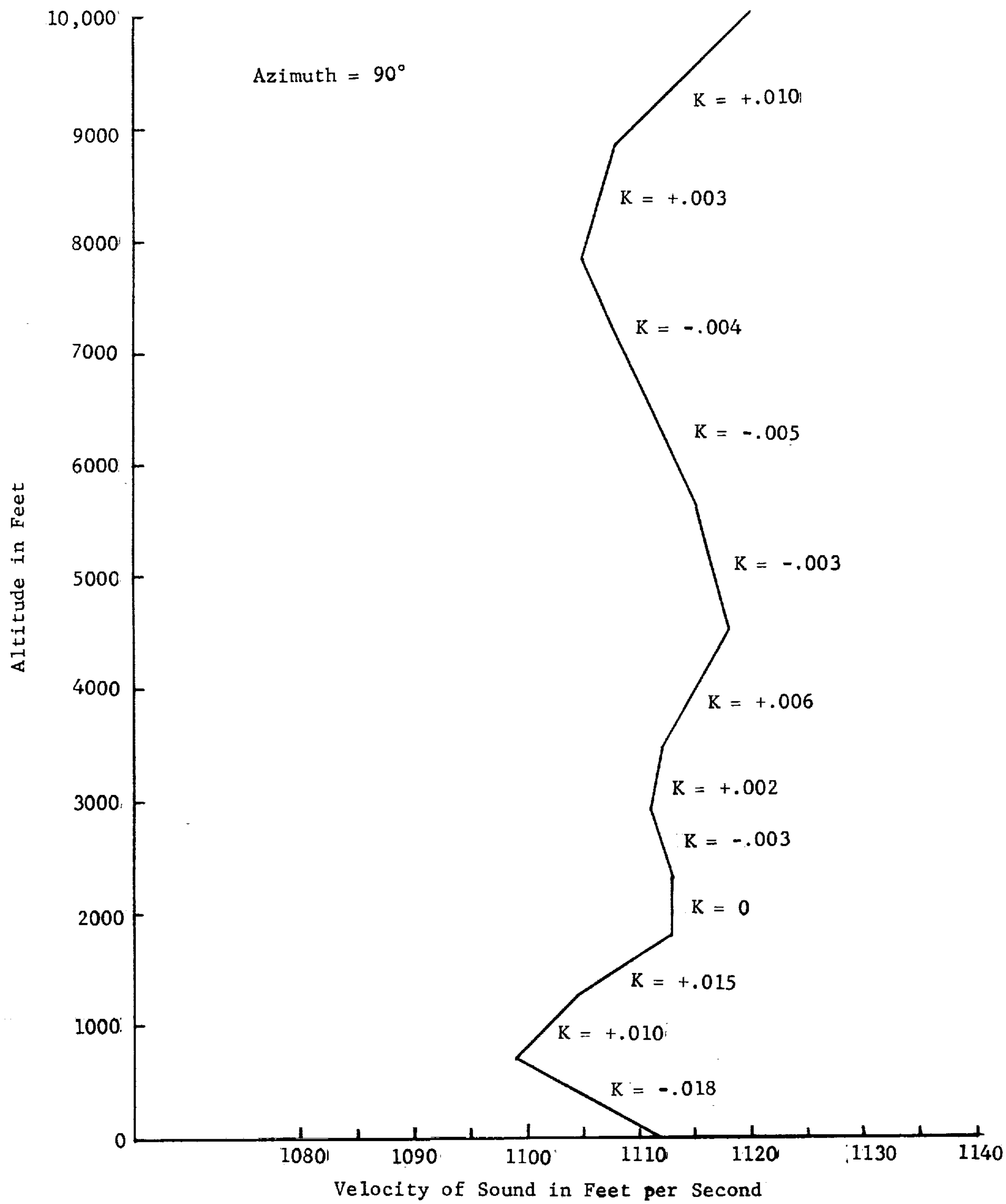


FIGURE 23. VELOCITY RANGE FOR 90° AZIMUTH

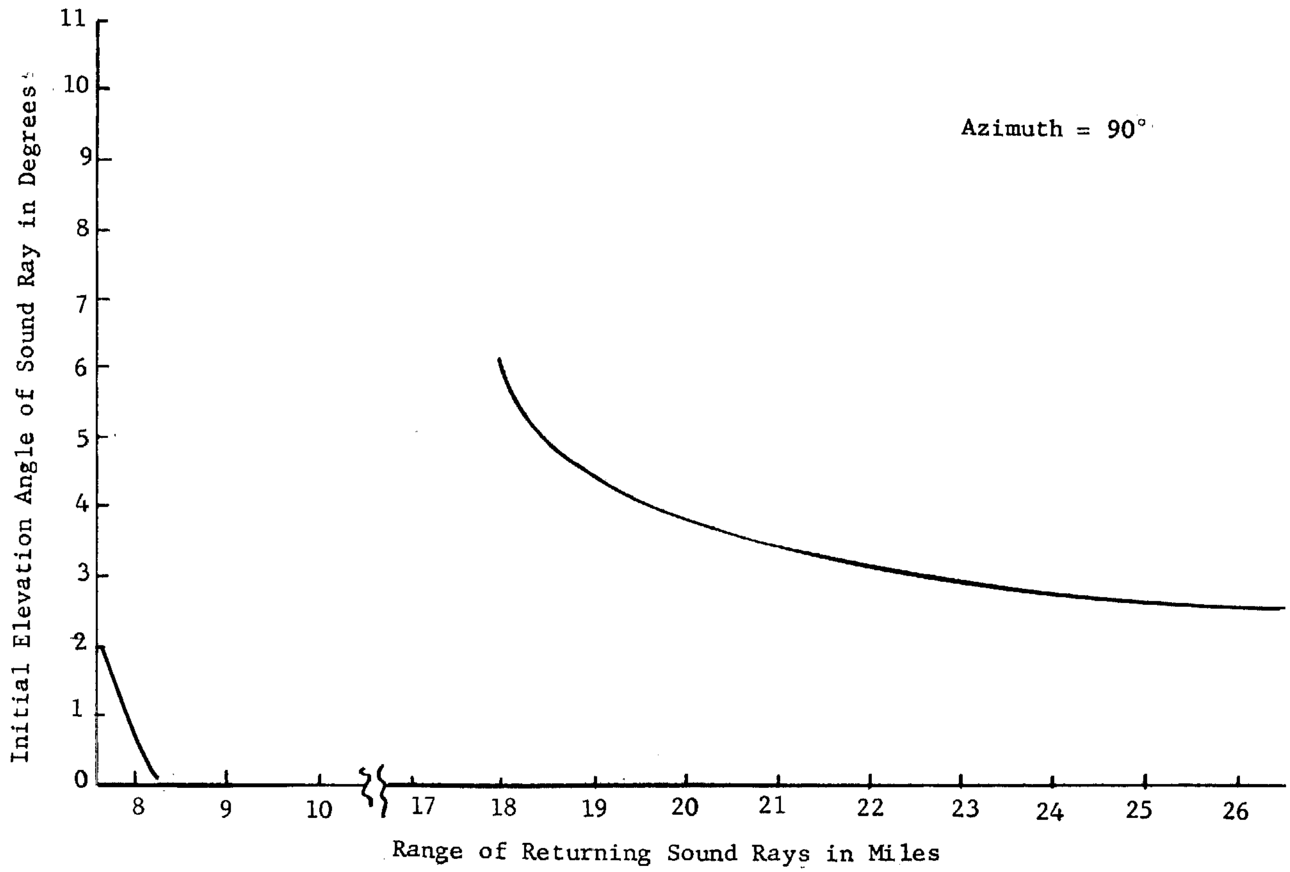


FIGURE 24. IMPACT RANGE FOR 90° AZIMUTH

TABLE I. METEOROLOGICAL DATA

(From BRL Report No. 1118)

Air Temperature °C	Altitude Above Surface (Feet)	Wind Direction From True North (Degrees)	Wind Velocity (ft per sec)
15.1	0	210	7.3
12.0	720	282	11
11.5	1200	342	16
11.0	1790	13	21
9.5	2320	21	21
9.5	2910	14	25
8.2	3440	21	28
6.9	4520	36	32
5.2	5600	36	34
3.0	6680	30	37
1.3	7820	28	35
0.9	8850	40	32
0.2	9700	51	40
-1.4	10750	55	44

FIGURES 18, 20, 22, and 24 are the range versus initial elevation angle plots computed at azimuths of 0° (north), 30°, 60°, and 90° (east) respectively, and they show the range in miles at which focusing occurs along these azimuths. The best technique for plotting this information in the plane of the earth's surface appears to be a topographical technique using lines of constant initial elevation angles. A plot of this nature is shown in FIGURES 25, 26, 27, and 28 which are maps of the Huntsville area with the sound source located at the origin. Data were computed at every 10° increment of azimuth angle from 0° (north) to 90° (east). FIGURE 25 has the lines of constant initial elevation angle for each full degree of evaluation angle, while FIGURE 26 has added each 3/4 degree in full degree increments. FIGURE 27 has added each 1/2 degree and FIGURE 28 has added each 1/4 degree (such as 1/4, 1-1/4, 2-1/4 etc.). Since these lines intersect each other, the total effect is a shading process at the areas on the map at which focusing of the sound ray occurs. These areas become darker and more filled in as more calculated rays are successively placed in position over the map. Areas of sound focusing at 0°, 30°, 60°, and 90° can then be checked against FIGURES 18, 20, 22, and 24 respectively. For example, at an azimuth of 60°, FIGURES 28 and 22 show the focusing to occur between approximately 5.3 and 5.9 or 6.0 miles, with very heavy concentration between 5.3 and 5.4 miles.

The shading (which occurs as lines of constant initial elevation angles are plotted) supplies a quick and easy method of determining where sound will be heard and where it will also cause damage. For instance, if the meteorological data used to compute FIGURES 25, 26, 27, and 28 were actually measured on a day of static firing at Redstone Arsenal, it could be predicted that Huntsville will hear the sound but will not sustain damage due to destructive focusing. On the other hand, gate 1, gate 8, and any dwellings approximately one mile north of the intersection of highways U. S. 231 and Whitesburg Drive will not only hear the sound but might sustain damages to windows, walls, etc.

The method which is now being used for plotting this information is explained in Section VIII. This simply shows the area in which sound will occur and does not indicate the areas of probable damage.

SECTION V. METEOROLOGICAL EFFECTS UPON TEST SCHEDULING

A. BACKGROUND

The Test Division of Marshall Space Flight Center realized that tests of the Saturn vehicle would produce sound with high energy at low frequencies. Knowing that this type of noise is capable of radiating long distances through the atmosphere with low losses, methods of avoiding alarm and annoyance caused by the tests were necessary.

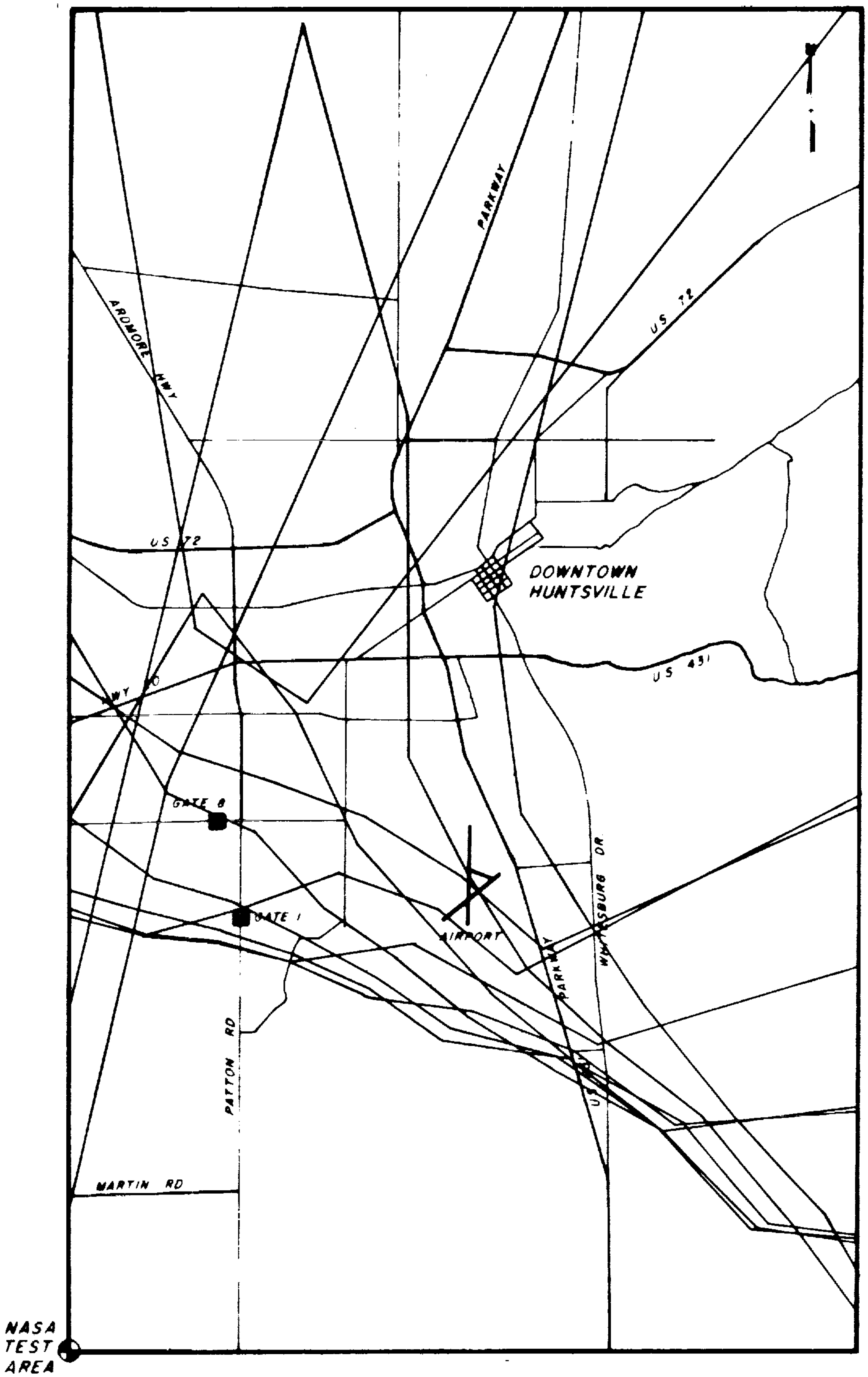


FIGURE 25. MAP OF THE HUNTSVILLE AREA

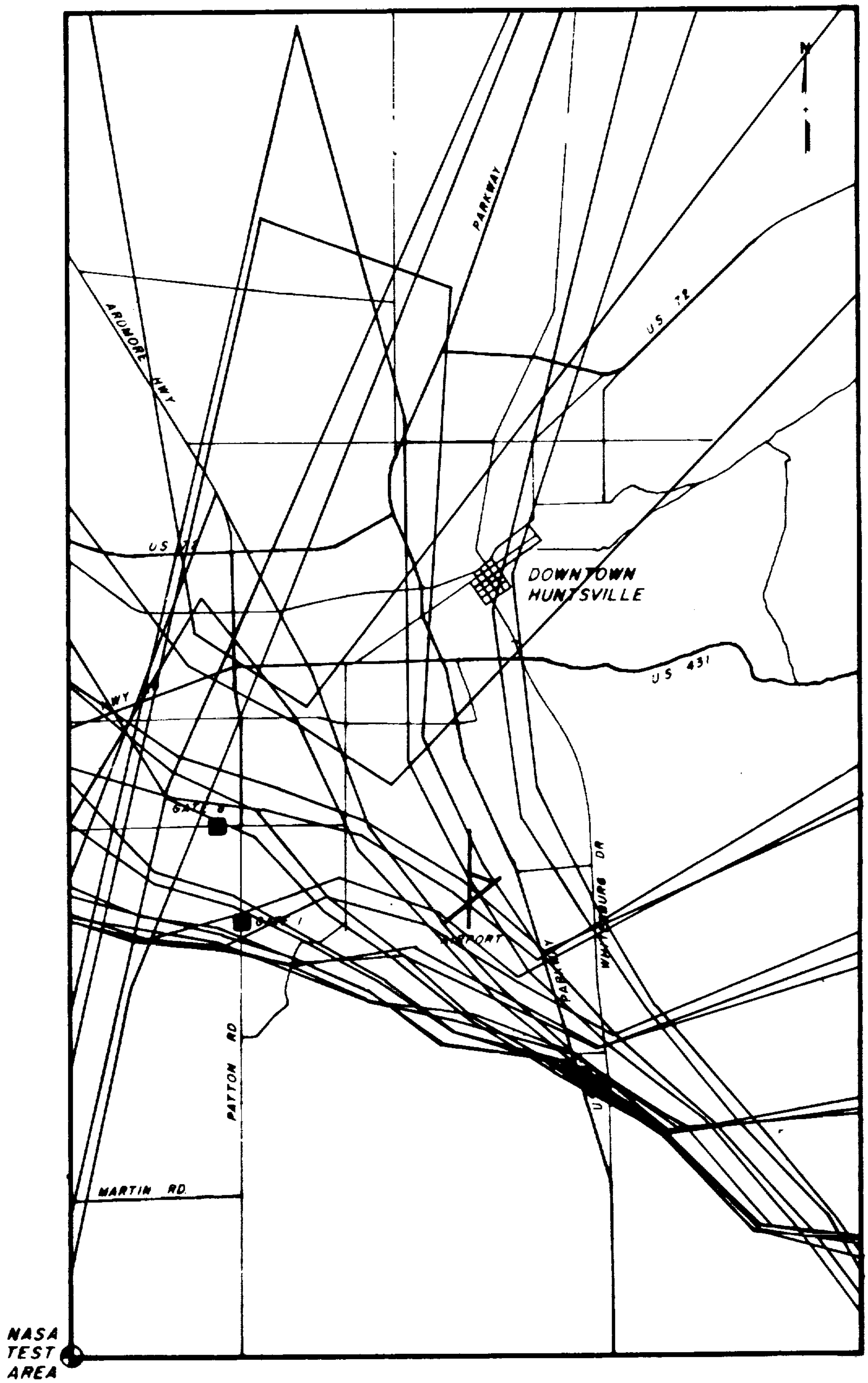


FIGURE 26. MAP OF THE HUNTSVILLE AREA

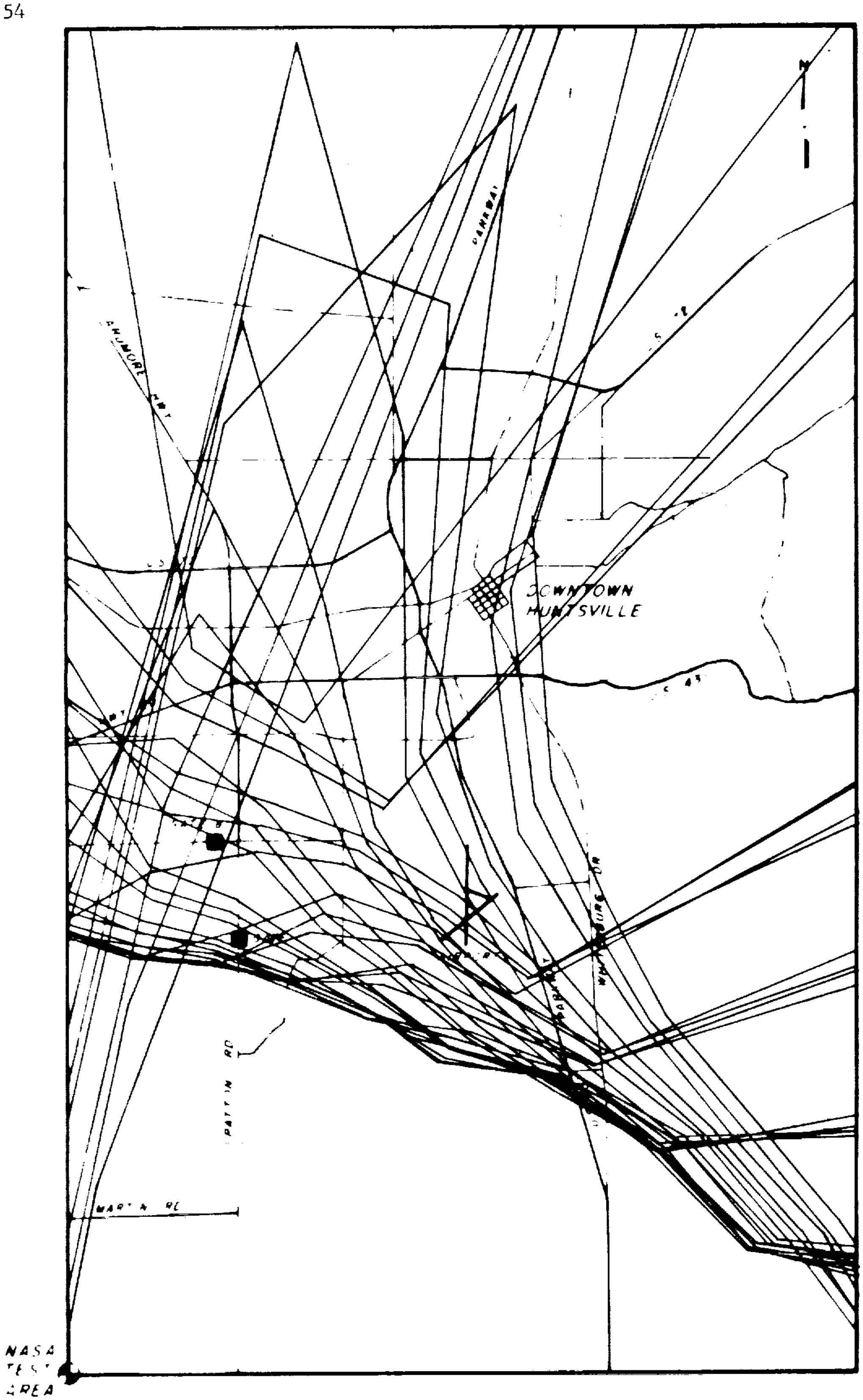


FIGURE 27. MAP OF THE HUNTSVILLE AREA

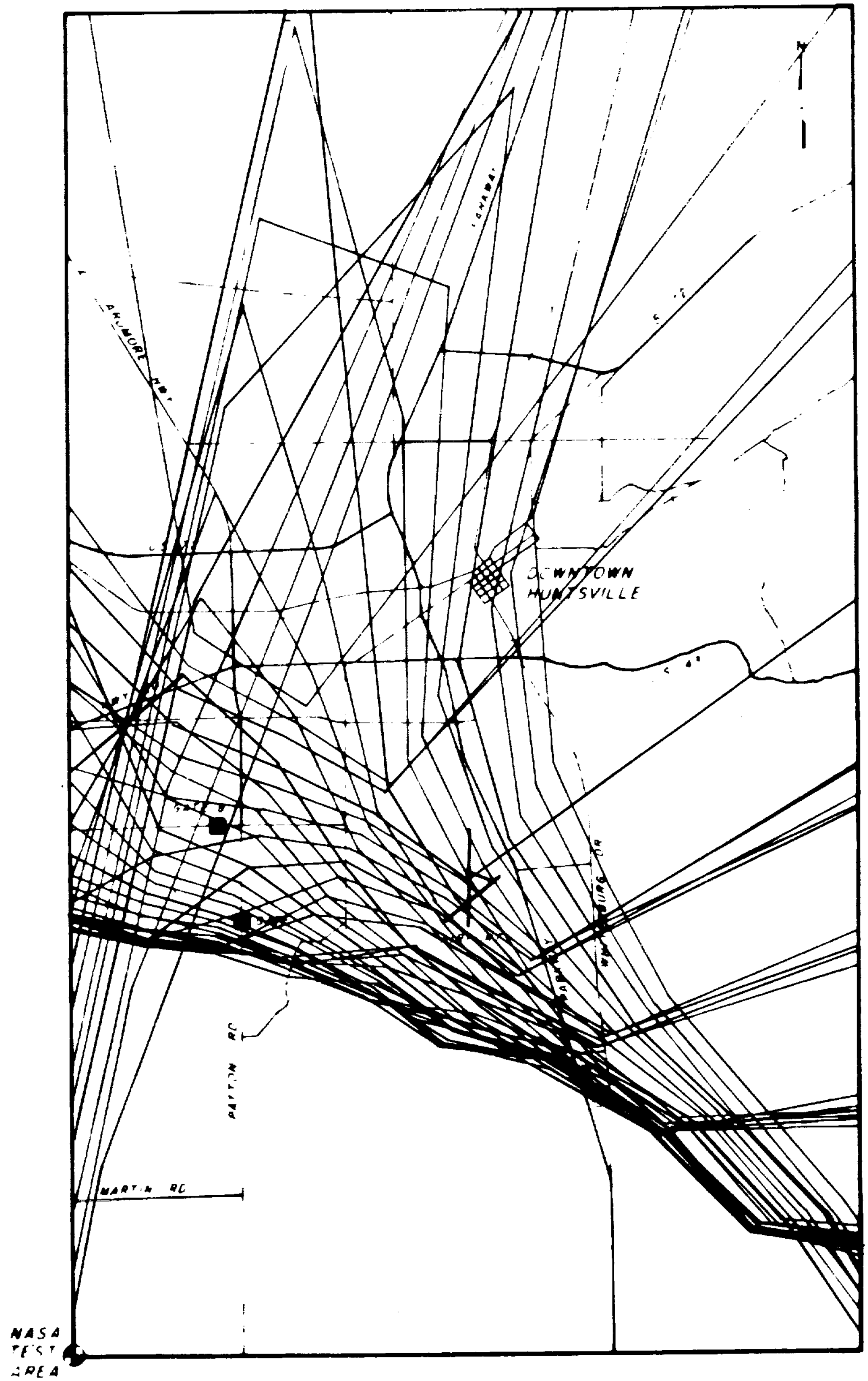


FIGURE 28. MAP OF THE HUNTSVILLE AREA

Considering the effects of the long range propagation as described in the previous sections, it was found during certain Saturn static tests that focusing of the sound generated during the tests did occur. Because the high frequency energy generated at the test site has been considerably attenuated by losses to the air, all the sound in the focus will usually sound like a tornado or thunder. Since much of the energy is in the sub-audible frequency range, the resulting building vibration causes the audible sound outside of buildings to seem less than the combined sounds inside of buildings. Thus, it can be seen that residents within the focus area may be alarmed and annoyed and might even believe that they are experiencing an earthquake.

B. EFFORTS AT CONTROL

To improve public relations with the neighboring residential communities, Test Division attempted to avoid testing the Saturn when atmospheric conditions conducive to focusing would exist. Referring to FIGURE 29, it was decided to test when a category "1" condition existed, whenever possible. Category "1" exists when the net wind and temperature effects cause the acoustic velocity to have a negative gradient, i.e., wind velocity from the residential communities and air temperature dropped with increasing altitude. To measure the climatic conditions existent prior to a scheduled test, the balloon soundings became important. Thus, the sound propagation conditions could be found and used to improve test scheduling to take advantage of category "1" conditions which might occur.

Experience gained from a study of the meteorological history of the area showed that category "1" or "2" conditions were quite common in the spring and summer with the coincident result that the entire first series of Saturn tests during the spring of 1961 passed with no complaints being registered by our neighbors. However, in the winter, weather conditions can change radically in a short time with the result that occasionally, in spite of efforts to schedule very carefully, the Saturn tests were made under what were considered unfavorable conditions (category 4 or 5). Naturally, the surrounding areas registered some alarm and annoyance, and MSFC took cognizance at the nature and seriousness to the response of the residents of the surrounding communities.

Because of the high noise level in the Huntsville area from Saturn test SAT-11 on December 20, 1960, and the numbers of reports of alarm and annoyance from residents, the services of a skilled weather interpreter or forecaster to help in test scheduling was considered necessary. In January 1961, such a forecaster's services were used. Despite a lack of good equipment, his interpretations aided the Test Division in delaying a scheduled test during very unfavorable conditions. However, on the date of test SAT-12, a significant shift of upper altitude winds occurred causing a general focus condition to form a short time prior to the test.

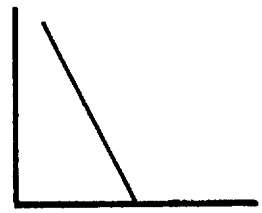
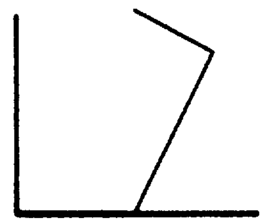
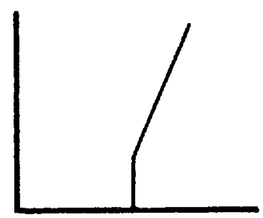
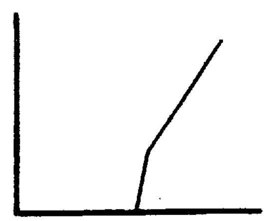
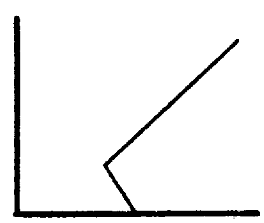
CATEGORY	DESCRIPTION		FACTOR
1	SINGLE NEGATIVE GRADIENT		0
2	SINGLE POSITIVE GRADIENT		5
3	ZERO GRADIENT NEAR SURFACE WITH POSITIVE GRADIENT ABOVE		10
4	WEAK POSITIVE GRADIENT NEAR SURFACE WITH STRONG POSITIVE GRADIENT ABOVE		25
5	NEGATIVE GRADIENT NEAR SURFACE WITH STRONG POSITIVE GRADIENT ABOVE		100

FIGURE 29. SOUND PRESSURE MULTIPLICATION FACTORS FOR VARIOUS TYPES OF VELOCITY GRADIENTS

Generally speaking, a sounding at X-2 hours showed a category "2" condition, and the sounding at test time, which was not plotted until an hour after the test, showed a category "3" or "4" condition. Reports received from the community showed that some areas had higher levels for SAT-12 than for SAT-11. Therefore, requirements for better measurements of atmospheric conditions and well founded weather estimates were deemed necessary to avoid repeated noise exposures of surrounding communities. This required the full time attention of an expert forecaster having access, through the best available equipment, to all of the applicable data from all parts of the country. Even though forecast service has been used for scheduling later Saturn tests, some instances of high sound levels in the neighboring communities have nevertheless occurred.

C. TEST REQUIREMENTS

Based on this experience, the Test Division's need for estimating stability of the conditions measured by the soundings was studied. The requirement for predicting, some time in advance, the effects of large-scale weather movements upon local conditions was also considered. In addition, the complicated nature of preparations involved in Saturn static testing advances stringent requirements on the estimation techniques.

To avoid the large expenses of unnecessary test cancelling, or possible claims on the government from damage incurred by testing, Test Division has established a procedure for test scheduling which requires:

1. Regular soundings of the atmosphere to establish trends of weather conditions are required. Also, several soundings on the day of test to facilitate favorable test timing and to authenticate forecast procedures are required.

2. Interpretation of all available weather data to predict the focal conditions on the test date is necessary. An estimate is required initially 3 to 4 days in advance of the test date, another 48 hours prior to date, and a final estimate is needed one day in advance. The one-day estimate is considered very important because test preparations can be held in an X-1 day status for 2 or 3 days but not indefinitely.

3. On the test day, accurate estimates of the stability of atmospheric conditions, established by the soundings, are required to fix the most favorable time for testing. It is known that the firing time can have a leeway of a few hours, but close estimates are considered necessary to reduce magnitude of reaction from the surrounding community.

As more reliable methods are developed for test scheduling, it is foreseen that static testing of large thrust Space Vehicles will be accomplished without exposing neighboring communities to the harassment of the annoying sound levels usually associated with the testing.

SECTION VI. METEOROLOGICAL DATA REQUIREMENTS

A. ROUTINE DATA REQUIREMENTS

Basic meteorological data required for short period prediction consist of accurate, representative vertical profiles of wind velocity and temperature, extending from the surface to 10,000 feet. On the basis of experimental ray tracing computations, it has been noted that in many instances even a difference of 1 fps in the value of a critical point on the sound velocity profile can move the focal range by several thousand feet and change the pattern of sound concentration near the focus. It is probably quite unrealistic to expect to attain sufficiently high sensitivity and accuracy in wind and temperature measurements so as to produce a sound velocity error as small as 1 fps. The spatial scale of the sound propagation phenomenon is some 10 to 15 miles; the scale of meteorological measurements should be representative of this value. Even if sensitive, accurate, and representative values of wind and temperature are available, the 30 to 45 minute time requirement for the data processing and sound ray prediction procedure still involves the use of a forecast technique, whether it involves merely the persistence of measured conditions or the extrapolation of a trend derived from serial observations. Even if the persistence forecast technique is used, a series of prior observations is useful in establishing limits of uncertainty for the areas of predicted sound return.

The routine data requirement for a long range prediction is more easily satisfied. The use of teletype circuits "A" and "C" and the standard facsimile circuit provides adequate surface and upper air data. In particular, facsimile charts of observed and forecasted wind and temperature conditions at 1000, 850, and 700 mb provide an excellent basis for 24-hour predictions of the general features of the sound velocity profile from the surface to 10,000 feet. Actual teletype reports of radiosonde observations (available twice daily) and of rawins and pibals (available four times daily) are used to analyze the more detailed structure at surrounding stations. Wind observations consist of speed to the nearest knot and direction to the nearest 10 degrees at 1000-foot intervals up to 10,000 feet MSL. Good analytical procedures can be used to make reliable 24-hour forecasts and useful 48-hour forecasts may also be possible.

The meteorologist must also be provided with the most detailed climatological survey as may be possible from the upper air records of neighboring stations, and from the year of GMD-1 rawinsonde observations taken by Army and MSFC personnel at Redstone Arsenal. The document, "Inferred Upper Air Temperatures and Winds over Huntsville, Alabama" (Ref. 15), prepared by the National Weather Records Center, under a contract with the Aeroballistics Division of the George C. Marshall Space Flight Center, provides a good beginning. A desirable second step would be an analysis of wind and temperature data to determine a detailed climatology of sound velocity profiles. A probability distribution of sound velocity gradients at 1000-foot intervals should be possible. Separate analyses of the initial heights, thicknesses and intensities of thermal inversions and of the boundary levels for significant positive and negative wind gradients would also be helpful. For simplicity, the initial analysis could be restricted to the azimuth line extending from the test stand to the center of populated areas in the direction of Huntsville (approximately 35°).

B. SPECIAL DATA REQUIREMENTS

In addition to the routine data collection for forecast purposes, a supplementary data gathering network is recommended for specialized studies. This network would comprise a mobile array of ground and free air sampling points. The data would primarily be used to analyze the extent and intensity of the atmospheric disturbances produced by the rocket exhaust and by significant orographical features. These and other possible applications have already been described in Section II-B. Very accurate, high response instruments and techniques will be generally required to analyze residual differences in atmospheric properties on a micrometeorological basis. However, there will be no necessity for telemetering to a central collection point or rapid data reduction. In most instances, a simple chart record will suffice for post mortem analysis. Remote, unattended operation should also be possible to achieve. For instance, small captive balloons could be used. Several balloons could be inflated and reeled out by a team of two men prior to a static firing or a test involving artificial sound sources. These same individuals could also take double theodolite observations during the actual tests. It is realized that the most difficult aspect of these special data collections probably lies in obtaining the services of a sufficient number of trained personnel.

C. VARIABILITY AND ERROR IN THE METEOROLOGICAL DATA

The importance of the basic meteorological data to sound propagation analysis has been stressed by Cox (Ref. 3), who states that "when transmission path lengths under condition are hecto or kilometers and meteorological data are obtained from instruments in common use, acoustical experiments should not be expected to check theory better than 60 to 90 percent". Sound as a rapidly propagated phenomenon, notices atmospheric inhomogeneities which cannot be practically observed by meteorological instruments in common use. It is possible, as Rothwell has done (Ref.10), to make post mortem corrections of the observed sound velocity profiles to account for the pattern of sound received at a down-range network of microphones. His results indicated that sizable corrections were often necessary to account for the observed sound patterns despite the use of a triple theodolite wind measuring system and accurate temperature determinations on towers and from aircraft. Although Rothwell ultimately concludes that the lower atmosphere is generally stable enough over a period of a few hours and at a distance, on the order of 10 miles, to justify refraction corrections, he does point out one of the very basic problems; "The boundary ray which determines the range becomes horizontal at some point in its path and small variations in sound velocity at the height of this point produce large changes in ray".

Naturally, the entire four-dimensional field of sound velocity is beyond feasible means of measurement. However, it is of great importance to carefully assess the probable errors in the meteorological data gathering system in order to estimate the probable errors in the position and intensity of the sound focus. If each sound ray forecast could be accompanied by a value expressing the calculated risk that a certain threshold of sound return might be exceeded over selected areas, a "go-no-go" decision could be made on an objective basis.

Any realistic appraisal of meteorological measurements must necessarily include the effects of variability, error, and representativeness. Variability refers to the fluctuations in temperature and winds which are associated with: (1) the synoptic cycle of migratory air masses, (2) the diurnal cycle of solar heating, (3) the effects of varying topography and ground cover, and (4) the effects of manmade sources of heat and momentum. Error refers to inherent limitations in sensitivity, calibration errors, positioning errors, and processing errors. Representativeness refers to the applicability of the meteorological data in terms of a time and space scale of measurement appropriate to the phenomenon under study.

Numerous tower, free and captive balloon, and airplane measurements have provided clear evidence that the atmospheric structure, especially within the lower 1000 feet or so of the boundary layer, is continuously varying as a result of eddy transport of heat and momentum. These eddies, which have a typical size range between 10 to 100 meters, are embedded within the larger scale circulation. As a result of solar heating during daylight hours, the intensity of this eddy activity is greatly enhanced, especially within the lower few hundred feet of the atmosphere, and the vertical profiles of wind and temperature are modified. Gustiness, or high frequency variations in wind speed over periods as low as a second or less, is a familiar phenomenon observed near the ground. To a gradually decreasing extent, gustiness is also present at higher levels in the troposphere. Free air temperature fluctuations are of lesser importance in terms of their effect upon the sound velocity profile.

Devyatova (Ref. 16) has presented a detailed analysis of the diurnal cycles of temperature and wind variations within the lower 3000 feet of the atmosphere (based upon several years of captive balloon observations taken near Moscow at 2 to 3-hour intervals on days with no large scale weather changes). The amplitude of the diurnal variations is shown to mainly depend upon the altitude and the season of the year. The amplitude of the temperature variation rapidly decreases with altitude and typically approaches approximately 1°C after the first 1000 feet. Amplitude of the wind speed variation is on the order of a few knots at all levels with a pronounced phase shift at approximately 300 feet. Below 300 feet the daily peak occurs in the early afternoon and above 300 feet the daily peak occurs shortly before sunrise.

For the purposes of this study, the eddy type changes in wind and temperature are a nuisance because they necessitate a sufficiently long time averaging period to eliminate the effects of random high frequency components. This problem can be handled adequately in the case of meteorlogical tower or captive balloon measurements by proper filtering techniques. However, in the case of conventional rawinsonde measurements, there is always an uncertainty factor present, especially in terms of the winds. Thus, it is often difficult to realistically interpret wind changes observed from successive rawinsonde observations (except for a statistical analysis of numerous observations adequate to determine a trend) since each observation contains random fluctuations. To some extent, the effect of small scale wind fluctuations can be reduced by decreasing the ascent rate of the balloon and thus increasing the time spent within a given altitude interval. Although this would increase the time lag between successive measurements within adjacent layers and reduce the "simultaneity" of the wind profile, each layer measurement would more closely approximate the proper time scale corresponding to the space scale of the propagated sound rays.

Some idea of the variability of wind as a function of time can be gained from Singer's analysis (Ref. 17) of a series of triple-theodolite runs made during a one-year period at Muroc, California. The data were obtained during daylight hours under clear weather conditions and therefore especially appropriate to this problem. The mean absolute value of the scalar speed error (averaged overall levels) was 0.4 knot, the smallest error obtainable for any free balloon wind measuring system. Over the interval of 3 to 9000 feet, the RMS vector difference was 2.6 knots for a 41-minute lag, 2.9 knots for a 63-minute lag, 4.5 knots for a 128-minute lag, and 6.3 knots for a 230-minute lag between observations. Gabriel and Bellucci (Ref. 18), as extensively quoted by Ellsaesser (Ref. 19), have analyzed the mean vector differences over lag periods of 1 to 10 minutes and 50 to 120 minutes from an extensive series of double-theodolite observations made at Fort Monmouth, New Jersey. These results are shown in Table II (Page 63).

It should be noted that the mean vector difference increases by a factor of 2 to 4 as the time lag is increased from 1 to 10 minutes to 50 to 120 minutes. Also of interest is the small mean error in double-theodolite wind measurements in the first 10,000 feet, 0.2 mph or less; above this altitude, the mean error increases rapidly to a value of 3.0 mph at 27,000 feet.

TABLE II. MEAN VECTOR DIFFERENCES BETWEEN WINDS MEASURED FROM SUCCESSIVE BALLOON FLIGHTS (IN MPH)

Altitude (1000's feet)	1 to 10 minutes	50 to 120 minutes	Mean Error
1	2.0	4.1	
2	2.2	3.7	
3	1.5	4.1	0.0
4	1.1	3.9	
5	1.2	5.0	
6	1.4	5.8	0.1
7	1.3	5.1	
8	1.2	5.0	
9	1.2	4.8	0.2
10	1.8	4.8	

The increase in wind error with altitude is characteristic of all theodolite, radar, and radio direction finding systems. Thus, such statistics as those prescribed by Ellsaesser (Ref. 19) for the average RMS error in 0 to 30,000 feet horizontal distance out or 6 to 46,000 feet altitude categories grossly overestimates the wind error in the lower 10,000 feet. However, Rapp (Ref. 20) has provided estimates of the error in GMD-1 wind measurements in 0.5 km intervals, based upon a series of flights at Belmar, New Jersey, each carrying two radiosonde flight units which were independently tracked by separate ground equipment. By combining his separate component values and changing the velocity units, the following values of probable vector error are obtained:

Height (km)	Vector Probable Error (Knots)
0.5	0.8
1.0	1.2
1.5	0.9
2.0	0.9
2.5	1.4
3.0	1.1

The probable vector error distribution increases rather sharply above 10,000 feet. Therefore, the wind data requirement falls within a preferred region of observational accuracy, with an average vector probable error of 1.1 over the entire altitude interval. It is believed that this error could be reduced by a factor of 1/2 by triangulation using two GMD-1 tracking units.

It is somewhat more difficult to assess the accuracy of wind speed measurements from captive balloons. Neither Devyatova (Ref. 16) nor Jones and Butler (Ref. 21) specifically mention the accuracy of their anemometer and air meter instruments for wind speed measurements, but it can reasonably be assumed from the basic properties of the instruments that the error was kept below 1 mph by taking proper care in suspending and exposing the equipment. Jones and Butler used vane anemometers capable of measuring mean wind speeds over a minimum time of one minute. In addition, sensitive Ower airmeters were used, which measured wind speeds over an average period of 2.5 seconds. Some slight error is introduced into wind speed measurements from the changes in height resulting from the natural motions of the captive balloon. Except during extreme conditions of vertical wind shear, this type of error is negligible.

The concept of representativeness in meteorological measurements has been carefully examined by Arnold (Ref. 22), in connection with weighted winds for artillery projectiles and rockets. His principal concern is with the vertical representativeness of wind data in terms of the variable nature of the wind-influence function on vertically rising vehicles. One important idea which he suggests is deliberately adjusting the ascent rate of a free balloon to provide wind data weighted in accordance with the operational requirements. This concept may also have some application in this case, since the vertical wind (and temperature) profile is of more critical interest in the lower few thousand feet. A simple type of ballast dropping device would permit longer and more detailed sampling of the lower levels.

The entire problem of representative sampling of atmospheric parameters is rather complex. The solution involves the proper choice of sampling points in the horizontal and vertical and the provision for sufficiently long sampling periods. It should be recalled that the sound propagation phenomena of concern in this study involve a space scale of some 10 miles and a time scale on the order of 1 to 3 minutes. Meteorological data are required which are truly representative of these scales. Thus, one instantaneous vertical profile of sound velocity derived from wind and temperature data would not be necessarily representative, due to the effect of random high-frequency fluctuations and instrumental error. However, there are two general types of solutions to the problem: (1) to obtain a representative space-mean vertical profile by making soundings of temperature and wind from several ground points, and (2) to obtain a representative time-mean vertical profile by making a sufficiently long-period sampling of atmospheric conditions from one observational system. In the next section of this report, the capabilities of several measuring systems will be discussed in terms of these two possible types of solutions.

SECTION VII. METEOROLOGICAL SYSTEMS

A. INTRODUCTION

To make the sound impact predictions, it is necessary to know some of the prevailing meteorological conditions. Basic parameters of interest are the temperature and wind velocity as a function of altitude. Knowing these data to an altitude of 10,000 feet above terrain is generally sufficient.

The systems examined fell into two basic types. The first type used free balloons; the second used captive balloons. Other systems were given only cursory examination.

The basic systems are discussed within this section of the report. The discussion of free balloon techniques includes the background and operation of the present ground meteorological detection systems and a brief review of the plans and activities of the various design and user groups. Special systems for use at George C. Marshall Space Flight Center will also be discussed.

Meteorological systems using captive balloons will be discussed from the instrumentation viewpoint.

B. FREE BALLOON SYSTEMS

1. Rawinsonde Systems

Within the last twenty-five years, the rawinsonde system has developed from crude beginnings to a system which is in wide use by the Weather Bureau and various military services. The Rawin Set AN/GMD-1 and the Radiotheodolite WRBT-57 are radio direction-finding sets, operating in the VHF range. They are radio theodolites which track the signal transmitted by a balloon-borne radiosonde combined with a receiver for decoding intelligence from a radiosonde signal.

The AN/GMD-1A Rawinsonde system consists of Radiosonde AN/AMT-4 Rawin Set AN/GMD-1A, and a meteorological recorder (Radiosonde Recorder AN/TMQ-5, Radiosonde Receptor AN/FMQ-2, or Radiosonde Receptor AN/FMQ-1) which make up an integrated upper atmosphere sounding system.

The radiosonde consists of a transmitter, modulator, antenna, battery and pressure, and temperature and humidity sensing elements which are carried aloft by a gas-filled rubber balloon. The 1680 megacycle transmitter is modulated at an audio frequency rate with a blocking oscillator. The frequency of the oscillator is determined by the resistance of the temperature and humidity sensing elements, and the resistance of the reference resistor located in the grid circuit. The pressure sensing element consists of an aneroid cell which drives a commutating switch. The switch alternately connects the temperature and humidity elements into the modulator circuit as pressure varies with altitude.

The Rawin Set, AN/GMD-1A automatically tracks the balloon-borne radiosonde to altitudes of 100,000 feet or more, and to horizontal distances of about 125 miles, depending upon the surrounding terrain. The Rawin set indicates and records the azimuth and elevation angles of the radiosonde, and these angles can be plotted with the height (computed from the temperature, humidity, and pressure data) to determine wind direction and wind speed. This set receives and amplifies the signal from the radiosonde and passes this signal to the meteorological recorder.

The meteorological recorder accumulates pressure contacts, temperature, and humidity data on paper tape in the form of divisions, which are related to the transmitted modulation frequency by the factor one-half (100 cps equal 50 recorder division).

The system just described was satisfactory compared to the methods previously used for upper air soundings, but it still had three specific deficiencies:

a. The radiosonde transmissions were of a serial nature, dependent upon the position of the commutator arm being driven by the pressure sensor. To be completely sure of the pressure level being transmitted, it was necessary to maintain a complete record of all data transmitted up to the time under consideration. This was no problem, except during periods of signal fading, where data were not complete. Such instances required judgment and extrapolation of the data by the operator who was never absolutely sure of data validity.

b. The pressure sensing element in the sonde was an expensive part and required an individual calibration curve for each sensor. The aneroid cell was subject to considerable inaccuracy at low pressures and was subject to hysteresis and response lag.

c. Data received by the ground station had to be reduced to a useable form with considerable manual effort before it could be used as the basis for weather forecasts.

The GMD-2 system appears to overcome the above deficiencies. This system makes use of the GMD-1A Rawin set for tracking the radiosonde and incorporates new features to improve and simplify the gathering of upper air data.

The radiosonde was modified to eliminate the aneroid cell. The temperature, humidity, and reference elements are sequentially introduced into the grid circuit of the blocking oscillator with a motor-driven commutator. A 403 megacycle superregenerative receiver is included in the sonde, the output of which is used to frequency modulate the 1680 megacycle transmitter in the radiosonde. This combination created the remitter-radiosonde.

A ranging attachment was developed which, using the remitter feature of the radiosonde, provides measurement of the slant range between the ground station and the radiosonde. A 403 megacycle transmitter is modulated by a signal of 81.94 kc and is beamed to the radiosonde which retransmits the 81.94 kc signal to the ground. Measurement of the phase of the transmitted signal compared to the phase of the signal received from the radiosonde results in the indication of slant range. This ranging attachment is the CM63 GMD-2 Comparator.

In addition to the CM63 comparator, a Control Recorder was developed to use the slant range data to compute true altitude by means of an electromechanical analog system consisting of potentiometers, resolvers, and synchros.

The Radiosonde Data Computer, later called the Meteorological Data Computer CP-204 GMD, was developed under a contract to the Signal Corps. This computer utilizes altitude output of the Control Recorder, together with audio frequency data from the receiver (temperature, humidity, and reference frequencies), to compute true temperature, humidity, and pressure. Subsequent models of the computer were modified such that the equation solved was for D value (Slant Range in feet) where the computed outputs were temperature, humidity, D value, and pressure altitude. This computer was an electromechanical analog device.

The Zone Wind Computer was developed to compute winds aloft, that is to compute average wind speed and average wind direction over various layers of the atmosphere. This computer was also an electromechanical analog system.

The Control Recorder, Zone Wind Computer, and the Meteorological Data Computer developed under these contracts were generally satisfactory, but they display four basic deficiencies:

d. The equipment was all electromechanical analog, and modifications necessary to update the system in accordance with newer information required major redesign in many areas.

e. Cost of system was high; a feature inherent in any precision, electromechanical analog device.

f. The system lacked coherence from the standpoint of presentation. Each equipment had its own printed record and they varied from the unitary decimal system used on the Meteorological Data Computer to straight digital as recorded with printing counters.

g. The equipment required that a human operator take the data, decode the significant points of inflection of temperature and humidity lapse rate, and transmit the significant data to the teletype network.

The GMD-2 is now in production, with several stations expected to be in use by both the U. S. Air Force and U. S. Navy.

Developments on new meteorological systems are progressing at the Weather Bureau, U. S. Army, U. S. Navy, and the U. S. Air Force.

2. Weather Bureau

The Weather Bureau is replacing the old SCR-658 Rawin Set with the new Radiotheodolite WRBT-57.

3. U. S. Army

The Meteorological systems designers at the U. S. Army Signal Research Development Laboratory at Fort Monmouth, New Jersey, are designing and evaluating advanced systems. The GMD-3 system is a semiautomatic atmospheric sounding system. In this system, some of the meteorological data from GMD-1 equipment are converted automatically into the digital computer format on punched paper tape. Remaining data are read from the radiosonde recorder by an operator who punches these data onto a second paper tape. Data from both tapes are then entered into a digital computer. The computer performs the various meteorological calculations and types out the final answers as a function of altitude. An engineering model of the GMD-3 system is being evaluated and has not been placed in production.

The ultimate system in which all data will be handled automatically is being actively pursued, but has not reached the evaluation stage.

4. U. S. Navy

As mentioned earlier, the Navy is planning to use the GMD-2 at their shore stations. The problem of shipboard meteorological data gathering and processing is being studied. Work is in process to redesign the radiosonde and receiving station to provide a printed record of temperature, pressure, and humidity. Winds-aloft observations are made by radar tracking of a balloon containing chaff.

At the Pacific Missile Range, data from the GMD-1 and -2 are entered into a digital computer after undergoing some manual processing. The computer then computes and produces the meteorological data as a function of altitude.

5. NASA Wallops Island

At this facility, data from the GMD-1 are placed in tabular form by the operator. Punched cards are then prepared. An IBM-650 digital computer performs the meteorological computations.

6. U. S. Air Force

As part of the 433L weather forecasting system, the CV-692 GMD Radiosonde Data Converter is being developed. This unit will use a combination of analog and digital computer techniques to process data from a GMD-2 Rawin Set. This unit provides a teletype output for transmission of data to the weather network.

At the Atlantic Missile Range, data from the Rawin station located at Cape Canaveral and from down range Rawin stations are transmitted by teletype to the weather central at Patrick Air Force Base. At the central weather station, a digital computer is used to compute the meteorological data.

7. Special Free Balloon Systems

Several special free balloon systems were considered. Two of these are discussed in the following paragraphs. Other systems such as radar tracking of a balloon-borne radar target were also considered.

a. Single Radiotheodolite. FIGURE 30 is a block diagram of an automatic sound prediction system using a modified radiosonde and a standard Rawin set such as the AN/GMD-1, -1A, -1B, -1C, or -2. The Rawin set is unmodified, except for the paralleling of the azimuth and elevation synchro leads. A digitizing section is shown in considerably greater detail than the rest of the diagram. This section takes the GMD data and converts it into digital form for computer application. If the digital computer is "off-line", then a means for temporary storage of the data and subsequent readout into the computer would be provided. Computer output is fed to a X-Y plotter, where the areas of sound focusing are plotted.

A standard radiosonde would be modified as follows: The usual altitude sensor would be removed and replaced with a General Mills digital altimeter. FIGURE 31 illustrates a mockup of this combination. This altimeter uses a pair of aneroid capsules to move a contact across the surface of a rotating code drum. Some 200 individual code characters would be included in the range from 0 to 10,000 feet. A suitable code would be used such as octal coding using the Gray system. A separate set of synchronizing contacts also would be included on the end of the code drum.

The idea of increasing the sensitivity of the radiosonde in the lower altitudes was presented by Gifford (Ref. 23). The Gifford unit, which was used for soundings of 8,000 feet, employed two thermistors in series for greater temperature sensitivity, added aneroid cells and an enlarged baroswitch frame.

The use of a slower ascent rate would provide more detailed and representative sampling of the temperature and wind fields, as demonstrated by the detailed inversion study described by Gifford, wherein a slow ascent rate of approximately 500 ft per min was used. A slower ascent rate perhaps as low as 200 ft per min would greatly improve the quality of the wind measurements since not only would a longer time averaging period be possible within a particular height interval, but the winds could be averaged over smaller height intervals without increase in error. As has been suggested by Arnold (Ref. 22), an initially slow but gradually increasing ascent rate produced by a ballast dropping device could be profitably used to increase the sampling time within the lower 1 to 2000 feet, where, at the present time it is felt that significant details of the wind distribution are not being detected.

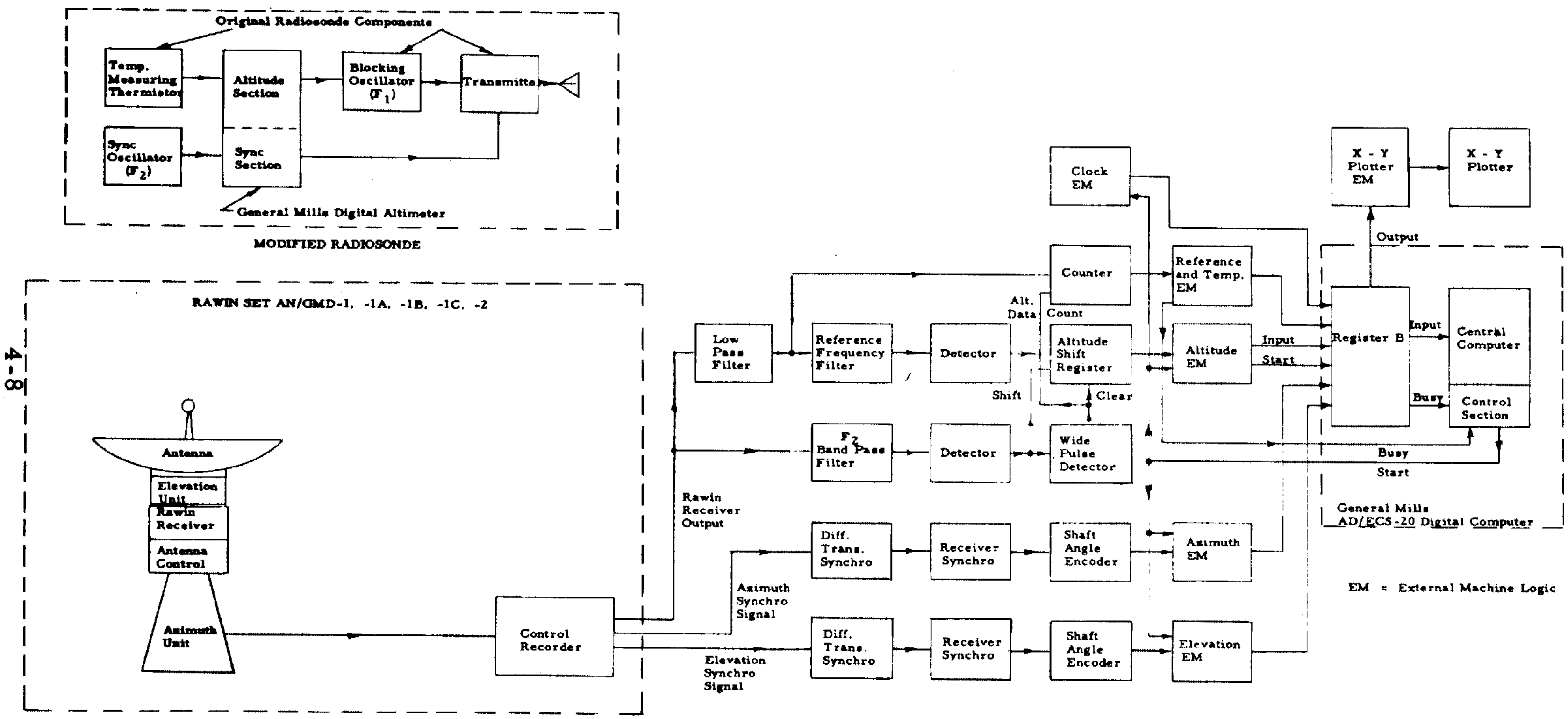


FIGURE 30. BLOCK DIAGRAM, AUTOMATIC SOUND PROPAGATION PREDICTION SYSTEM

FIGURE 31. MOCKUP OF RADIOSONDE WITH GMI DIGITAL ALTIMETER

Another area of possible improvement involves the choice of the representative release point for the balloon. Since rawinsonde measurements are made along the trajectory of an ascending flight unit, it is obvious that the data represent a variable space scale depending upon the wind distribution. The best solution might involve the use of a variable release point between the test stand and the City of Huntsville.

In the usual radiosonde, temperature is measured by a thermistor which is part of the frequency determining circuit of a blocking oscillator. A reference frequency is generated by shorting out the temperature-measuring thermistor. FIGURE 32 is a partial layout of the surface of the code drum. Shaded areas indicate metallic portions; all other areas are of insulating material. In the modified radiosonde, the temperature-measuring thermistor would be shorted out by the altitude contact on the code drum. Thus, during the code characters and the reference frequency area, the oscillator would be operating at its reference frequency of about 200 cycles per second. During the other portions, the oscillator would be at a frequency determined by the ambient temperature. This blocking oscillator modulates the transmitter. For purposes of synchronizing, a second oscillator would be added to the radiosonde. This oscillator would be transistorized and operated on a frequency of approximately 2 kc. The output of this oscillator would be fed through the sync contacts to the transmitter.

The Rawin set receives the signal from the radiosonde. The Rawin set automatically tracks the radiosonde in azimuth and elevation. Synchro transmitters are geared to the elevation and azimuth mechanisms. Synchro repeaters provide dial indications on the control recorder. The same information from the synchro transmitters would be fed through external differential transformer synchros and to receiver synchros. The shaft angle of the receiver synchro would be converted to a digital signal by means of a shaft angle encoder. The reason for the differential transformer synchro is to provide a means of setting the shaft angle encoder to the actual setting of the antenna. Mechanical means are provided within the control recorder for setting the dial indicators. Thus, without modifying the Rawin, except for adding parallel connections on the synchro leads, we have achieved a digital representation of the azimuth and elevation angles. The Rawin receiver output contains the original modulation presented to the transmitter; namely, the two audio tones generated by blocking oscillator and sync oscillator. The receiver output is fed to the low-pass filter and the F_2 bandpass filter. This filter allows the 2 kc signal to proceed to the detector. The detector provides a signal which is the envelope of the burst of tone. This signal is used to provide a shift pulse to the altitude shift register and also a signal to a circuit called the wide pulse detector. The wide pulse detector provides an output only when a wide pulse has been received. Output of the wide pulse detector is used to clear the altitude shift register and to provide a start pulse for the counter. The low-pass filter

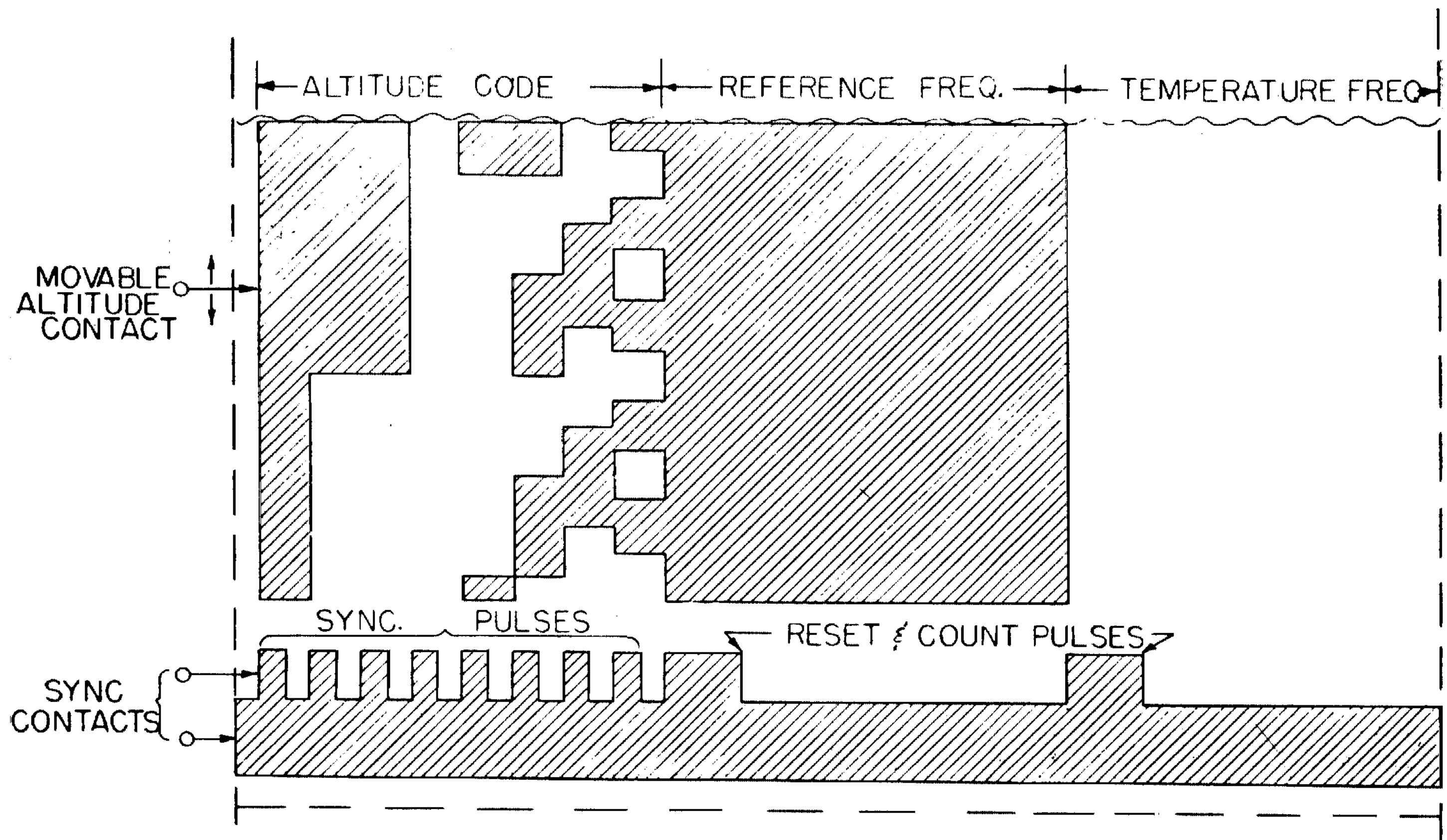


FIGURE 32. CODE DRUM LAYOUT

removes the synchronizing signal from the Rawin receiver output, and the filter output is fed to the counter. While the altitude contact is on in its insulated area of the code drum, and upon receipt of a wide pulse, the counter will determine the frequency of the blocking oscillator which is a function of the ambient temperature. Upon completion of the count, a signal is generated by the counter which is a digital representation of temperature. A similar action takes place while the altitude contact is on the wide metallic contact portion of the code drum. When the wide pulse is received, the counter determines the reference frequency. These two pieces of data, along with the initial calibration data, are used by the computer to determine the actual temperature.

Output of the low-pass filter is also fed to a second filter which permits only the reference frequency to pass through an envelope detector. The output of the envelope detector is a series of pulses which correspond to the altitude of the radiosonde at that particular time. These pulses are shifted into the altitude shift register in serial form. Upon receipt of the wide pulse, data from the altitude shift register are transferred in parallel form to the computer input equipment. A clock having a digital output is also connected to the computer input equipment.

In operation, the altitude time, temperature, reference frequency, elevation angle, and azimuth angle would be sampled at periodic intervals. The sampling interval would be on the order of one second. This rate was determined by the rate at which the balloon is ascending and the incremental altitude represented by one code group.

If the computer is operated "on-line", as soon as data are received, the computer will begin calculating the meteorological parameters as a function of altitude. Having calculated temperature and wind velocity as a function of altitude, the computer can then go into the second phase of operation where it actually computes the focal areas of sound and plots these areas on a map of the region.

The computer needs to be a small, ruggedized, general purpose computer which possesses numerous special input and output features which adapt it to control applications and other applications where external automatic equipment must be integrated into a system.

The computer must converse with numerous external devices if the appropriate synchronizing circuits are provided. These may include:

Typewriter	Card Reader
Printer	Magnetic Tape Units
X - Y Plotter	Analog Devices
Tape Reader	Control Systems
Card Punch	Displays

A "built-in" provision for real-time input and output would permit the user to order the compilation of data from any of several addressable sources and send control or data signals to several addressable destinations.

b. Double Radiotheodolite System. The double optical theodolite system is a well known technique for obtaining balloon trajectory, and winds-aloft data. This system has limitations and requirements which make it unsuitable for regular operational use. These limitations can be removed if a radio system is used instead of an optical system. With the radio system, the range is not limited by cloud cover. The radio system can be arranged to have automatic tracking with automatic digital readout of the azimuth and elevation angles.

The geometry of the system is illustrated in FIGURE 33. Location of the balloon can be calculated if any three of the four azimuth and elevation angles are known. The data relative to the positions of the two radiotheodolites are also required. By making these angle measurements simultaneously and periodically, the trajectory of the balloon can be calculated.

One fairly simple means for implementing this system would be to use two AN/GMD-1 stations. A conventional radiosonde could be used, or if desired, a modified radiosonde could be flown. To obtain the balloon trajectory information, only a transmitter need be carried. Since the position of the balloon is obtained mathematically, the altitude sensor can be eliminated. Since the effects of humidity on the sound predictions can be neglected, the humidity element can be eliminated. It is desired to obtain temperature and for this purpose the original temperature-measuring thermistor and blocking oscillator can be used. If the drift of the temperature measuring circuit is not excessive during the first 10,000 feet, it would not be necessary to read the reference frequency during the flight. However, it could easily be arranged to cycle the temperature measuring thermistor in and out of the blocking oscillator during the flight. This would yield a continuous inflight measurement of frequency drift. The usual meteorological recorder could be used to display the temperature data, or special ground equipment could be installed at one station to make the temperature measurement and convert it to the digital form automatically.

FIGURE 34 is a block diagram of a system which will automatically calculate the sound velocity and wind velocity as a function of altitude. Upon calculating the basic meteorological data, the computer would make the sound focal area calculations. Focal areas would be plotted automatically.

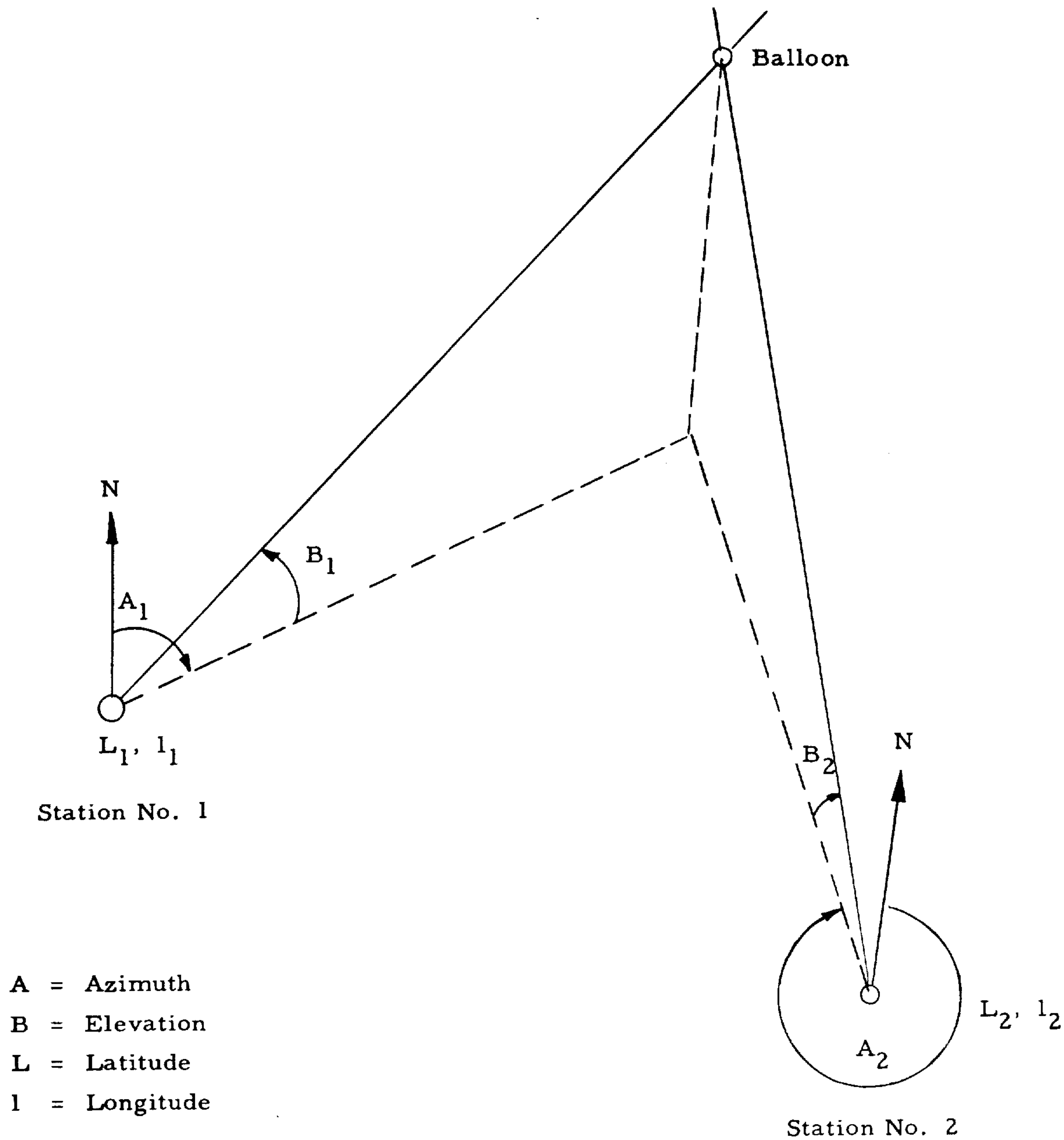


FIGURE 33. DOUBLE RADIOTHEODOLITE GEOMETRY

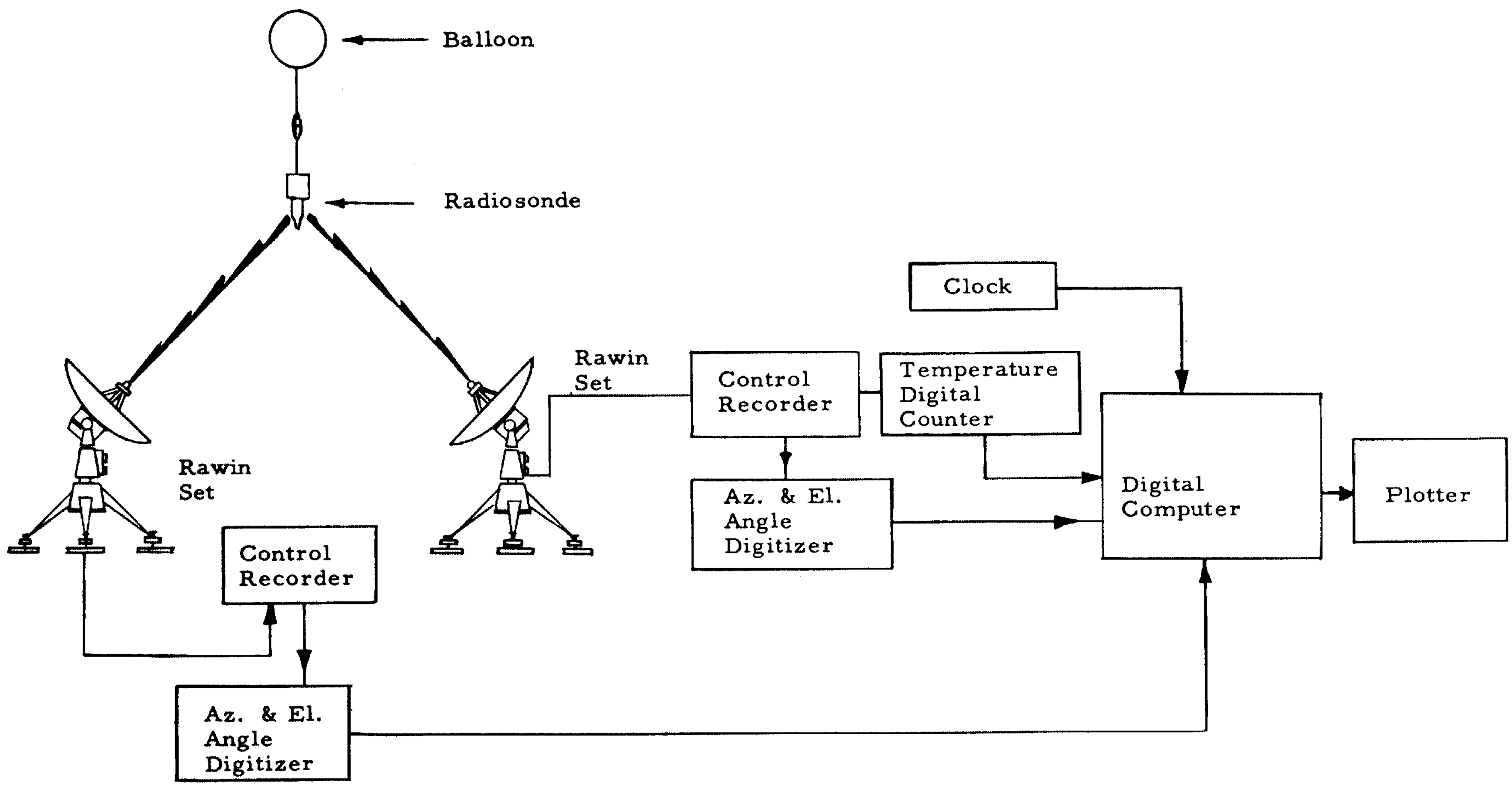


FIGURE 34. BLOCK DIAGRAM OF DOUBLE RADIOTHEODOLITE SYSTEM

In the simplest system, two GMD-1's could be used to obtain the data. With a minor modification, the two GMD's could be arranged to start from a common signal, thus assuring synchronism of their records. With the printing rate on the azimuth-elevation-time print out set at 10 per minute, a sample would be obtained for approximately every 100 feet of altitude with a conventional radiosonde. A slow rising balloon would allow a smaller increment of altitude between observations. The records from the GMD's could then be transported or otherwise communicated to a computer operator for entry into the computer. The computer would then calculate the meteorological data and the sound focal areas.

c. Tracking Radar. The position of the free balloon can be determined uniquely by using a single automatic radar tracking unit. The balloon would either contain or carry a radar reflector and a small temperature/telemetering transmitter. This method has the advantage of single station operation, similar to the single GMD, but the position determination will come from the purely geometric interpretation of the azimuth, elevation, and range as provided by the radar. In this latter respect, the method has the advantages of the double GMD in that no pressure sensing devices are needed on the balloon. For the free balloon system, the single station radar tracker combines the best features of the single and double GMD systems. Unfortunately, this system requires a precision radar which is neither available nor being planned for installation at the NASA test site.

d. Constant Level Balloons. Other specialized observational methods for research purposes include the use of constant level balloons or particle tracers for studies of local circulation effects. Angell and Pack (Ref. 27), for example, have recently described the use of metallized tetroons to study changes in wind circulation resulting from valley-mountain influences in the AEC Nevada Proving Grounds.

C. CAPTIVE BALLOON SYSTEMS.

Instruments borne by tethered balloons may be held at fixed altitude indefinitely and can present data on the time variations of the parameters being measured. This is a definite advantage over the free balloon which provides a single "run" of data. The tethered balloon or Aerocap system, which may be used in the proposed application could be one of two types; a large balloon supporting multiplicity of identical sampling instruments along its cable, or a small balloon carrying a single instrument at its base. In the latter case, the balloon altitude must be adjusted to the sampling level desired.

The captive balloon measuring techniques have the unique capability of providing continuous temperature and wind data at levels above those attainable by meteorological towers. Accurate temperature measurements have been made from captive balloons using thermistors (Ref. 21), ceramic rod elements (Ref. 25), and bimetallic elements (Ref. 16 and 26). By proper suspension and exposure of wind sensing units along the cable, accurate continuous measurements of wind velocity should also be possible.

The most sophisticated type of captive balloon system used to date is that described by Jones and Butler (Ref. 21). Measurements of temperature and wind speed were made at altitudes up to 7000 feet, using a series of three instruments suspended at intervals of 1000 feet. It should be possible to extend this method so as to make measurements at intervals of 500 feet or less.

While the temperature sensing method for a tethered balloon system will be similar to that for a free balloon, the wind measurement method is radically different. With a free balloon, the wind speed and direction are determined from the balloon positional data. Since a tethered balloon remains relatively fixed in position, it is necessary to carry some type of anemometer and wind vane at each sampling point on the cable.

1. Captive Balloon System with Multiple Sensing Points

A system of this kind will provide data which are fairly continuous in time and altitude. Its degree of time continuity will depend on the speed at which the sensing elements can be sequentially sampled, and the degree of continuity with altitude will be determined by the vertical separation between instruments.

a. Spacing and Total Number of Sampling Points. It is recommended that the vertical separation between instruments be no greater than 250 feet. This is expected to be sufficiently close for the most complex wind velocity profile that is expected. With the spacing fixed at 250 feet, the total number of instruments will depend on the required maximum altitude. While this was originally planned to be 10,000 feet, later evidence suggests that a much lower altitude may be sufficient. The distance from the test site to the sound focal zone of interest is from 50,000 to 80,000 feet. This zone includes the City of Huntsville. While it is not yet conclusive, there is strong evidence to suggest that for sound returns in this zone, the maximum sampling altitude may be limited to 5,000 feet. This would limit the number of sampling points to twenty, and would reduce the size of the balloon considerably.

b. Airborne Instruments. Identical instrument assemblies would be attached to the tether cable at the sampling points. These would measure wind velocity, wind speed, and air temperature at each point.

(1) Temperature. A thermistor would be used for temperature sensing. A fixed excitation voltage would be applied to a thermistor-resistor network to produce a dc output voltage which is reasonably linear with temperature.

(2) Wind Velocity. A dc self-generating, three-cup anemometer is the simplest means for sensing wind speed. Output is compatible with the temperature signal described above.

(3) Wind Direction. The measurement of wind direction from a point on the tethering cable presents a special problem which arises from the random angular orientation of the cable and the package. It is necessary to reference the vane direction with respect to some external object or field. The obvious references are: astronomical, magnetic, and radio. This astronomical reference is ruled out because of its part time appearance, caused by cloud cover and day or night changes. The magnetic field would be disturbed by the tethering cable, the current in it, and in the power leads. It is proposed that a pair of existing radio stations be used in directional references for the wind vane.

A simple tuned loop antenna, consisting of a small coil and ferrite core, will display a pair of sharp nulls in its sensitivity pattern. In conventional practice, one of the nulls is "removed" by combining (with proper phase shift) the loop signal with that of a signal from a sense antenna which operates from the electrostatic component of the field. Since this amounts to a second radio receiver, it is proposed that a second tuned loop be used which responds to a second existing radio station. It should be mentioned that these two radio "receivers" are very simple, consisting mainly of a pair of transistors for gain and a diode for detection. The ferrite loops and their electronic components will be attached to a rotatable mount which will be driven by a constant speed miniature dc motor. The fixed angle between the loops will correspond to the angle between the two radio stations selected, as measured at the test location. Using conventional coincidence circuitry, a single complete null will appear in the combined detected outputs of the receivers for each rotation of the assembly, and a fixed directional reference will exist. A second pickup, a very small coil, will also be mounted on the rotating assembly and will produce a pulse as it sweeps past a small magnet mounted on the wind vane. The wind direction will be deducted from the relative timing of these two events as the scanning assembly is rotated.

The radio stations selected should have good signal strength and should be permanently active. The low frequency range station at the Huntsville airport would serve well as one station. A second might be a broadcast station in the area. The signals from such sources will be strong, permanent, and will not be subject to fading or interference.

c. Data Transmission. It is necessary that the data appear in such a manner that they can be handled by a digital computer. Temperature and wind speed will appear as dc voltages from reasonably low impedance sources. Wind direction data will appear as sequential pulses on the temperature and wind speed channels. A pair of very lightly insulated leads, plus a common lead, will be extended along the entire tethering cable for transmission of the dc voltages corresponding to wind speed and temperature. In the idle state, these leads will not be connected to the instrument packs at the various sampling points. An automatic series of coded signals will sequentially connect each package to the leads via relays. The control signals will be combinations of discrete audio tones applied to the dc power lead or to a signal lead. In this way, it is expected that in approximately one minute all instruments in the series can be sampled and the data placed in the storage unit.

The dc signal leads will be permanently connected to a pair of standard high impedance digital voltmeters, located at the ground station. Pulse data relating to wind direction will be filtered off the dc leads and will be converted from a time ratio to a digital signal.

d. Power to Instrument Packages. The instrument packages will require 28 volts dc. Power will be furnished by a fixed supply on the ground via a 22-gauge copper wire in conjunction with the steel tethering cable. It will be necessary to over supply the lower end of this power cable to overcome the effect of line resistance in the case of the more remote instrument packages. Accordingly, each package will contain a Zener type voltage regulator circuit, designed for 28 volts at its output point. Power will be drawn only by that package which is active and furnishing data; the others being idle. This will limit the cable line drop to that which can be compensated for by the regulators. A small battery will be included with each package for operation of the decoding circuit and activating relay.

2. Small Captive Balloon with Single Sensing Point

Instrumentation for the single point system would be similar to that of the multipoint system, except that only one unit would be required. It would be necessary to shift the altitude of the balloon to the various sampling levels, and this would naturally limit the speed at which a complete sampling could be made. There are a number of obvious simplifications that would be gained by using the single point system. The size of the Aerocap would be considerably reduced along with the support apparatus. Since there would be only one instrument package, no coded sequencing system would be required and data from the single instrument would be truly continuous in time.

D. MISCELLANEOUS SYSTEMS

1. Meteorological Tower

If a large radio or television tower should be available at a suitable location, installation of temperature and wind sensors at fixed points would provide the best possible type of detailed information within the first several hundred feet of the atmosphere. Fine scale studies could be made of the turbulent fluctuation in both horizontal and vertical wind. Power spectra and interlevel correlation studies could also be made. It must be realized, however, that an adequate instrumented meteorological tower system involves considerable capital outlay and high operational costs for the proper reduction and analysis of data. It would not be recommended that such a system be installed, unless the tower were to extend to a height approaching 1000 feet.

2. Rocketsonde

Most of the rocketsonde work to date has been slanted toward getting a payload to an altitude above 100,000 feet. A parachute is deployed at peak altitude, and the payload transmits its meteorological data while descending on the parachute.

The ARCAS rocket is perhaps the best example of such a system. The basic vehicle is a low cost, low acceleration rocket developed by the Atlantic Research Corporation. The single stage rocket is capable of delivering a 6.5-pound payload to an altitude of 200,000 feet. A 24-foot diameter parachute is used. Instrumentation is designated as AN/DMQ-6, which is a repackaged version of the AN/AMQ-9 radiosonde. The radiosonde is tracked on its way up as well on the way down, by a Rawin Set AN/GMD-2, which also provides the means for receiving the meteorological data. Tracking information obtained during parachute descent is interpreted as wind data.

The Cooper Development Corporation has developed a booster and dart combination called the ROKSONDE. The booster and dart projectile separate due to drag differences at booster burnout at approximately 4,000 feet, and the dart projectile coasts to over 100,000 feet. At a predetermined time, the fuse ignites a charge, and the payload of aluminum chaff is expelled to form a radar reflective, wind sensitive target that can be tracked with radar and provide a wind profile as the chaff descends.

Both of the above systems use a solid propellant fuel. Another approach has been developed by Texaco Experiment Incorporated. Their rocket, named Cricket, uses a cold propellant to boost the rocket to an altitude of 3,000 feet. At peak altitude a parachute is deployed which allows the whole unit to descend intact. The propellant is acetone and dissolved CO_2. A 0.5-pound payload can be carried and the rocket is reuseable at least 10 times. The launch system is simple and can be safely operated by untrained personnel. With additional altitude and payload capabilities, this system might well be adapted to the problem at hand.

SECTION VIII. LONG RANGE ACOUSTIC MEASUREMENT OF SATURN NOISE

In addition to monitoring the meteorological conditions before and during Saturn tests, MSFC personnel must also translate those conditions into a go-no-go decision. Since a large part of this decision is based upon where any acoustic focuses will occur and how high the sound pressure level may be within those focal areas, the weather information must be processed rapidly to give the two inputs.

First, the acoustic profile along the major azimuth from the test site through Huntsville is calculated and evaluated in accordance with the method outlined in Section V. In those cases where a category 3, 4, or 5 condition exists, detrimental focusing may occur in or around populated areas. To determine the effects of test firing under such conditions, a technique which uses standard ray tracing methods has been developed (Ref. 2) for determining the boundaries of receiver zones subject to meteorological focusing during long range propagation of acoustic energy. By plotting these areas upon specially prepared maps and using the multiplication factors shown in FIGURE 29, the results of a firing can be anticipated.

Over 50,000 calculations usually must be made in order to find the focal areas resulting from just the first 10,000 feet of meteorological data. For obvious reasons, the boundary zone problem was programmed for a digital computer. Recently, work has begun upon a computer program which will draw the focal zones directly upon the map.

The acoustic focal zone boundaries for Saturn tests SAT-01 through SAT-20 and SA-01 through SA-03 are shown in FIGURES 35 through 56. Test SAT-17 is omitted because it was too short to facilitate the collection of acoustic data. The meteorological profile calculated for a 35° azimuth is included on those figures. Since the computer utilization of the focal boundary zone technique was not available until the Saturn test series was well underway, several of the tests were made under less than ideal conditions, thus allowing acoustic data collection in a variety of circumstances.

Because of the wide range of azimuths from the Saturn Test Tower to the Huntsville city limits, only a small percentage of the tests were performed at times when no focusing at all occurred within the city limits. However, no evidence of refracted sound was found in the main "downtown" area in approximately 80 percent of the firings.

In order that the effects of meteorological focusing might be better understood and to check the theoretical basis for the multiplication factors used, MSFC personnel were assigned to monitor various locations with sound-level measuring equipment during later test periods. The results of these measurements are shown, along with the focal areas in FIGURES 44 through 56.

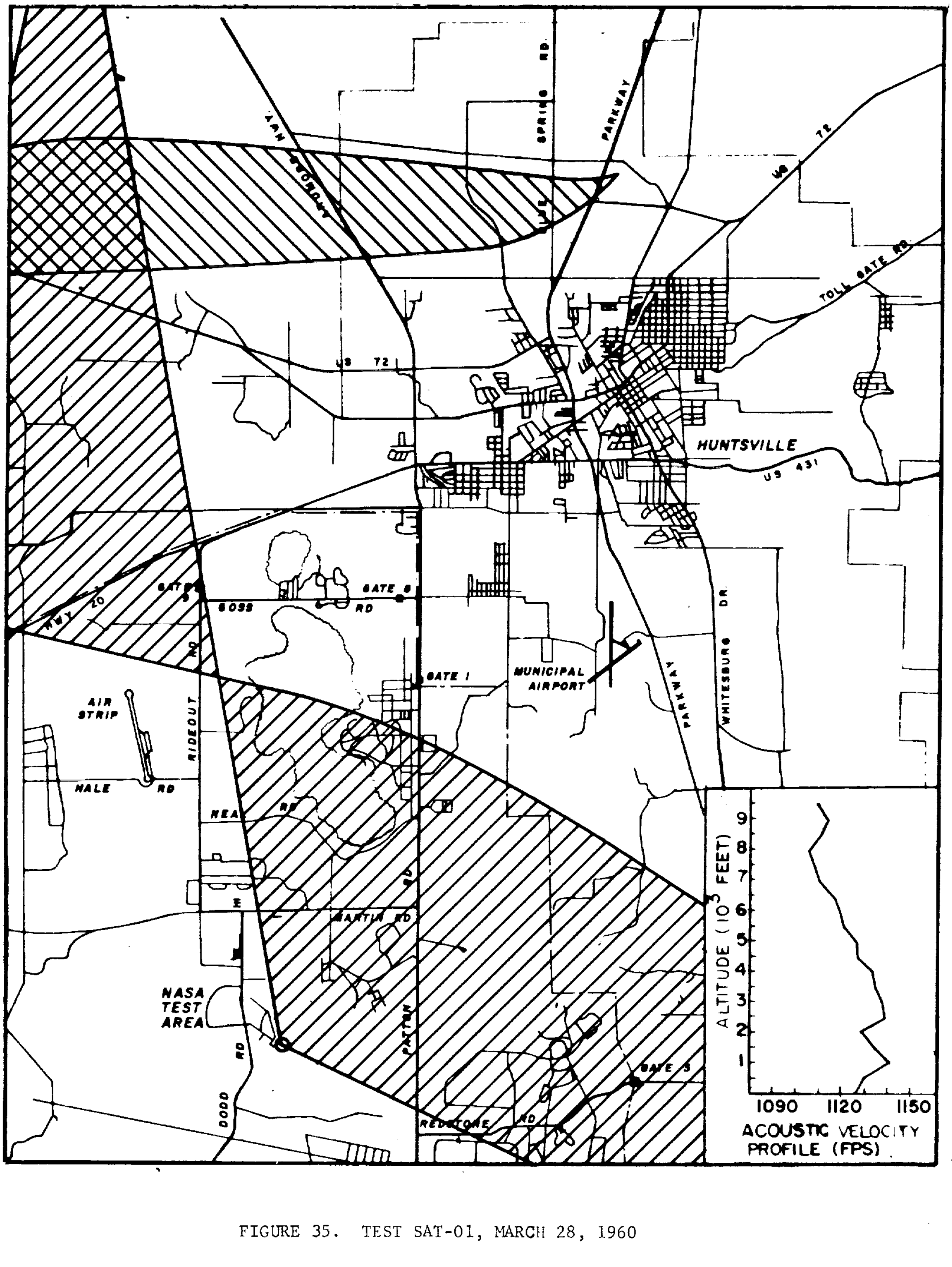


FIGURE 35. TEST SAT-01, MARCH 28, 1960

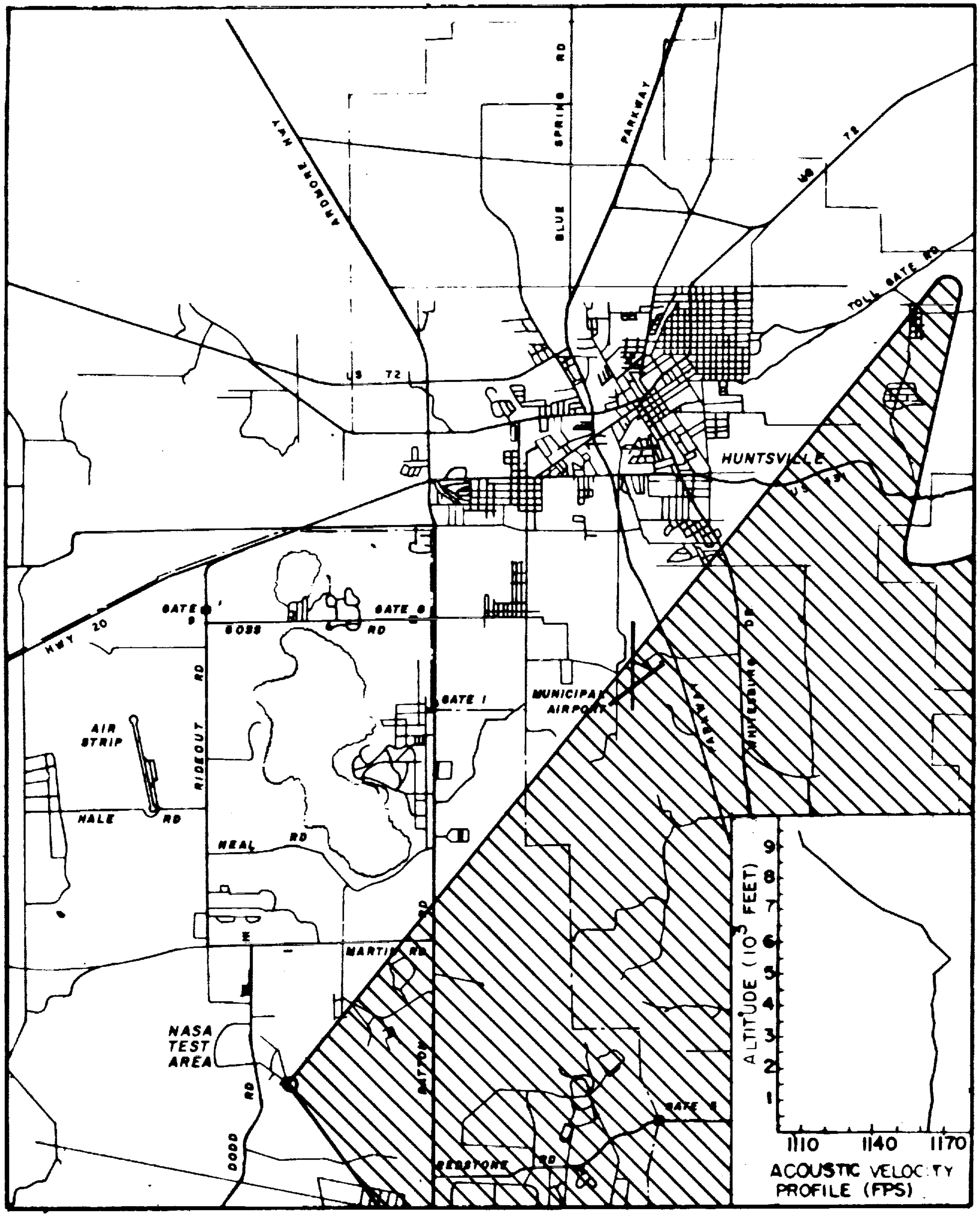


FIGURE 36. TEST SAT-02, APRIL 6, 1960

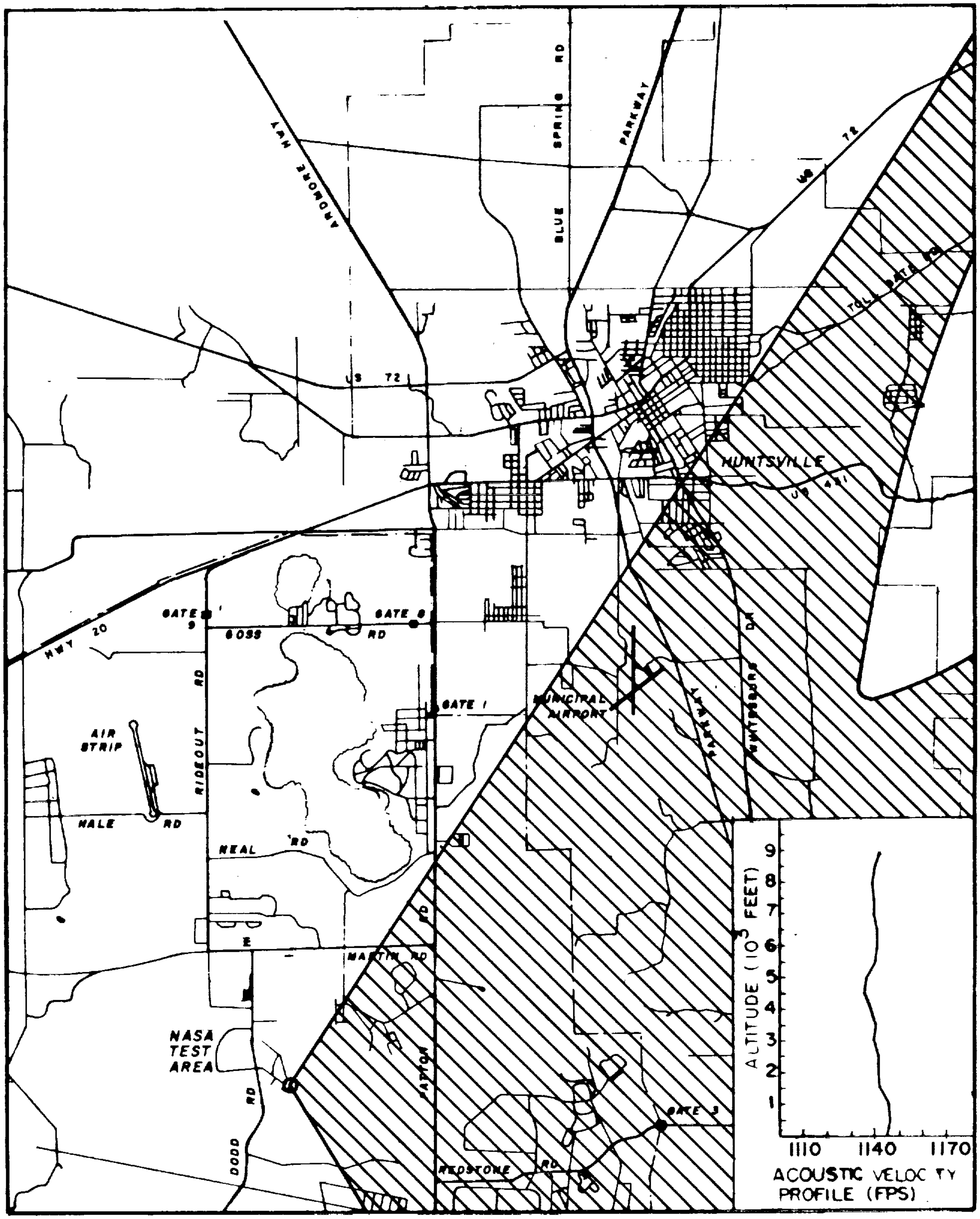


FIGURE 37. TEST SAT-03, APRIL 29, 1960

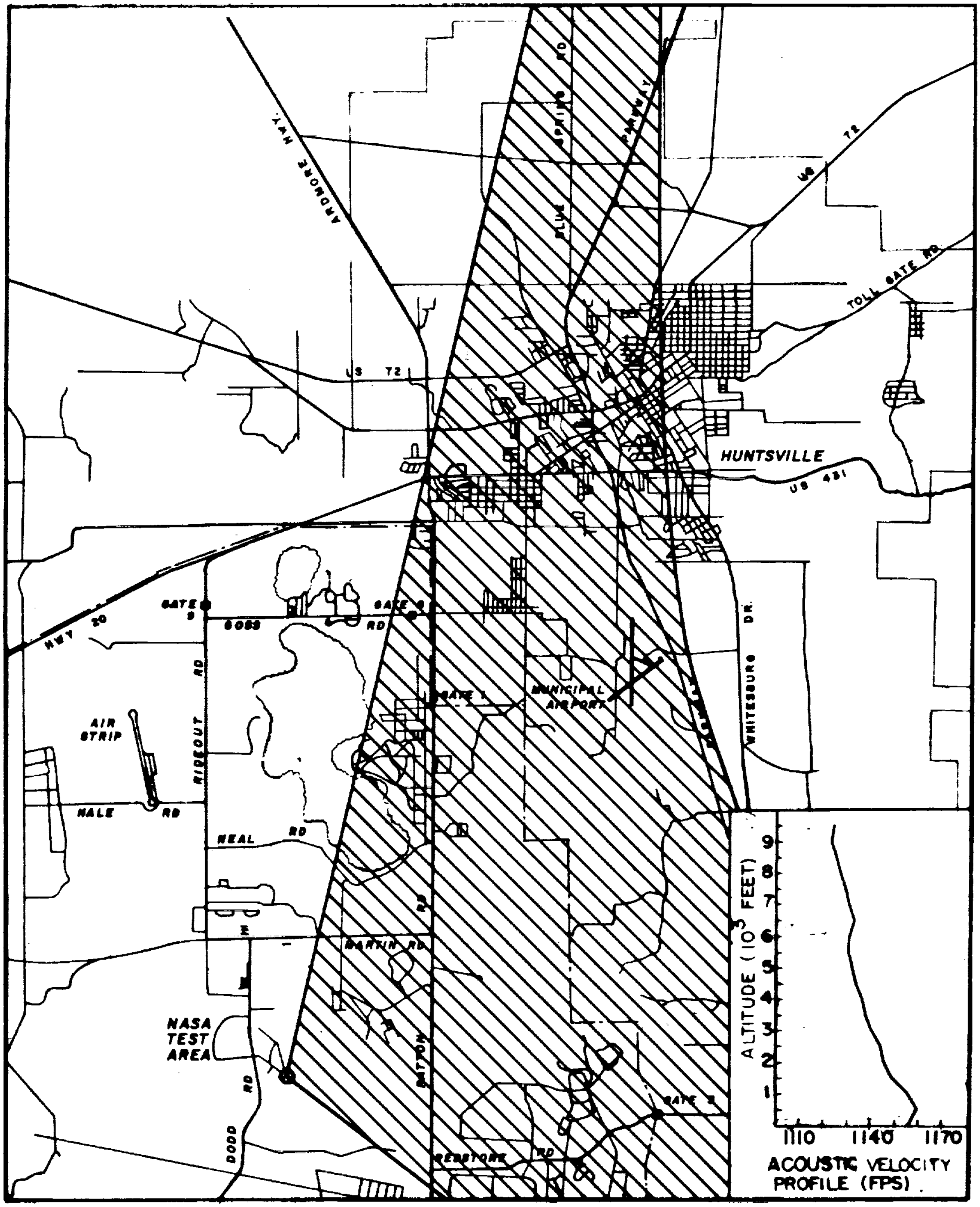


FIGURE 38. TEST SAT-04, MAY 17, 1960

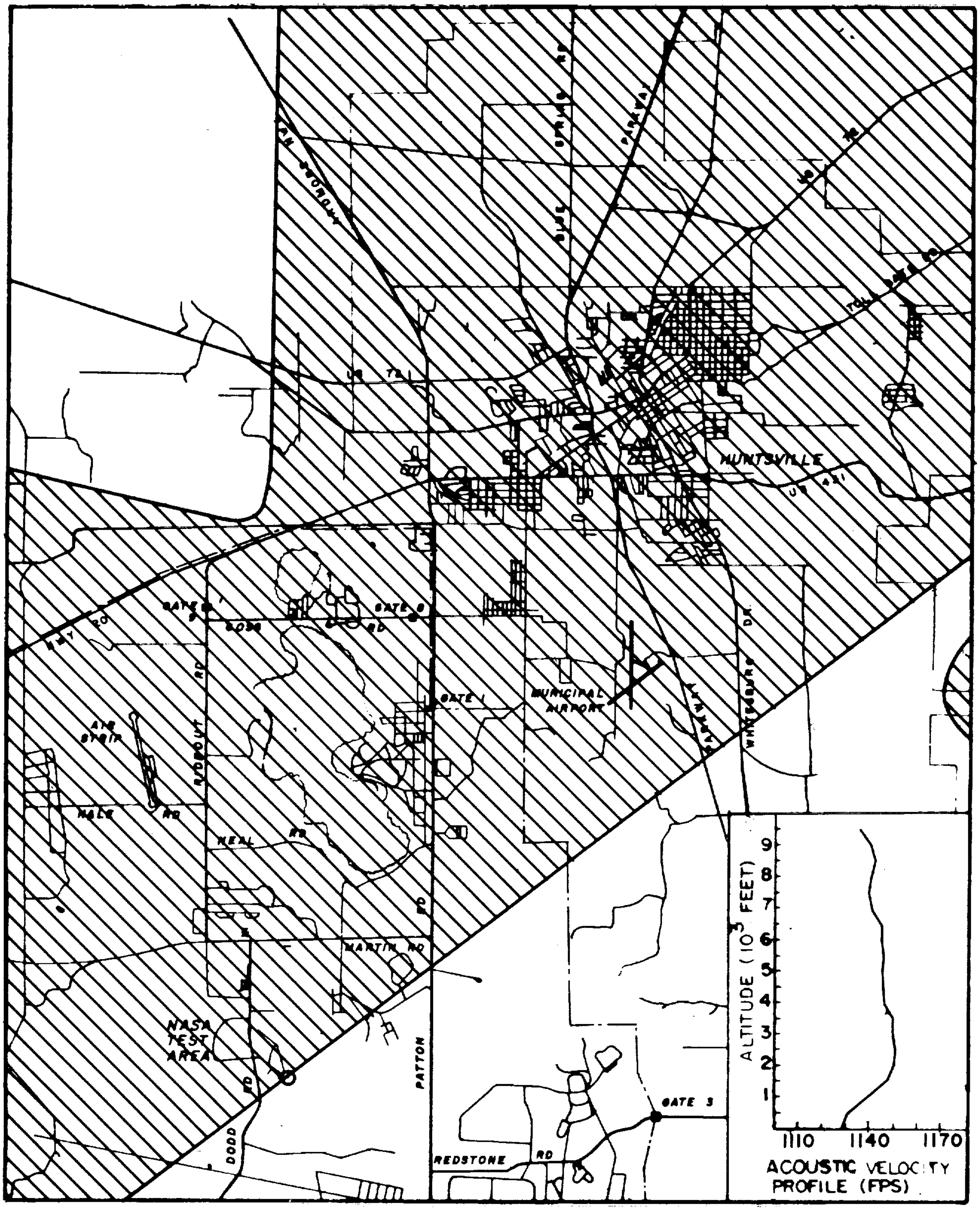


FIGURE 39. TEST SAT-05, MAY 26, 1960

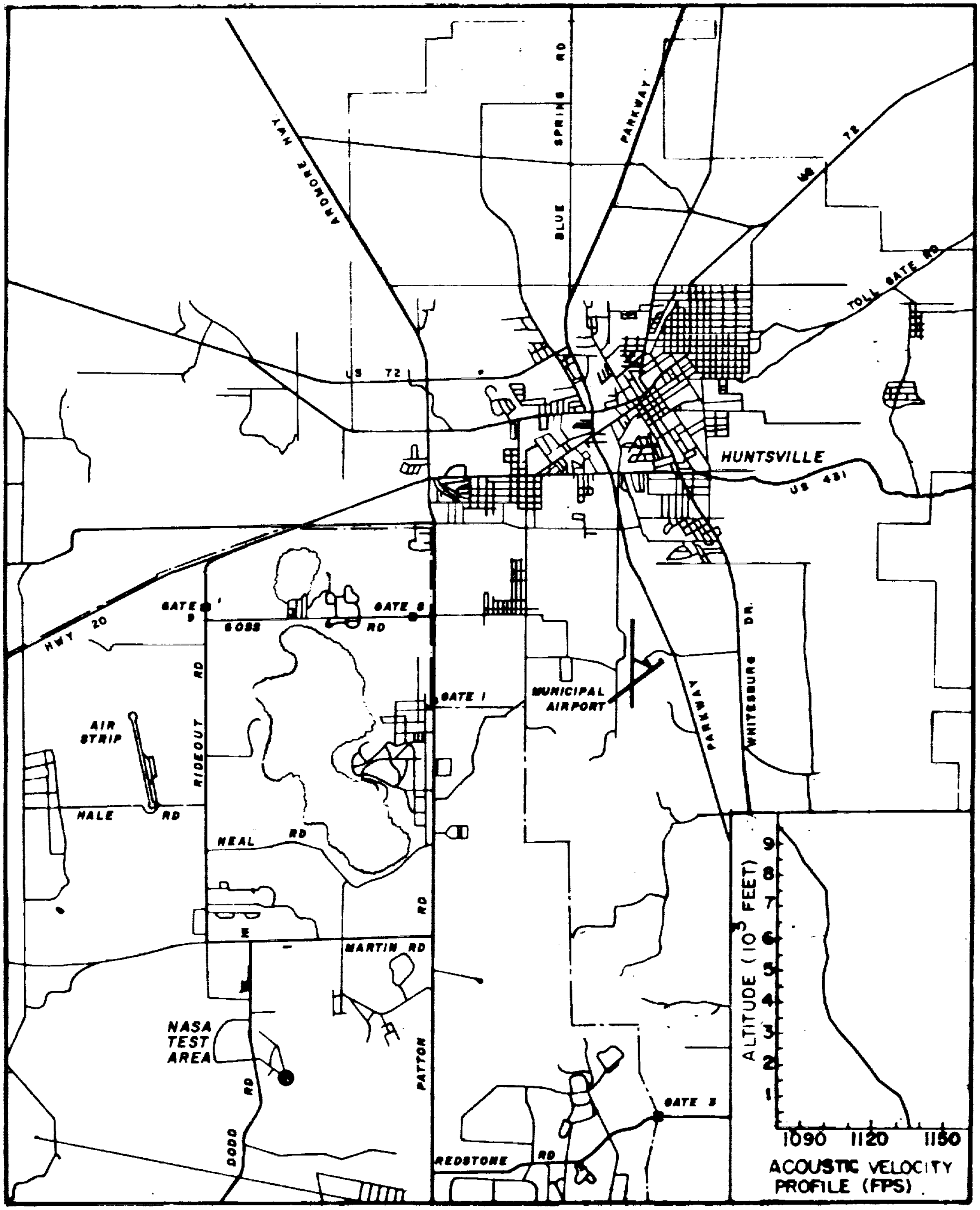


FIGURE 40. TEST SAT-06, JUNE 3, 1960

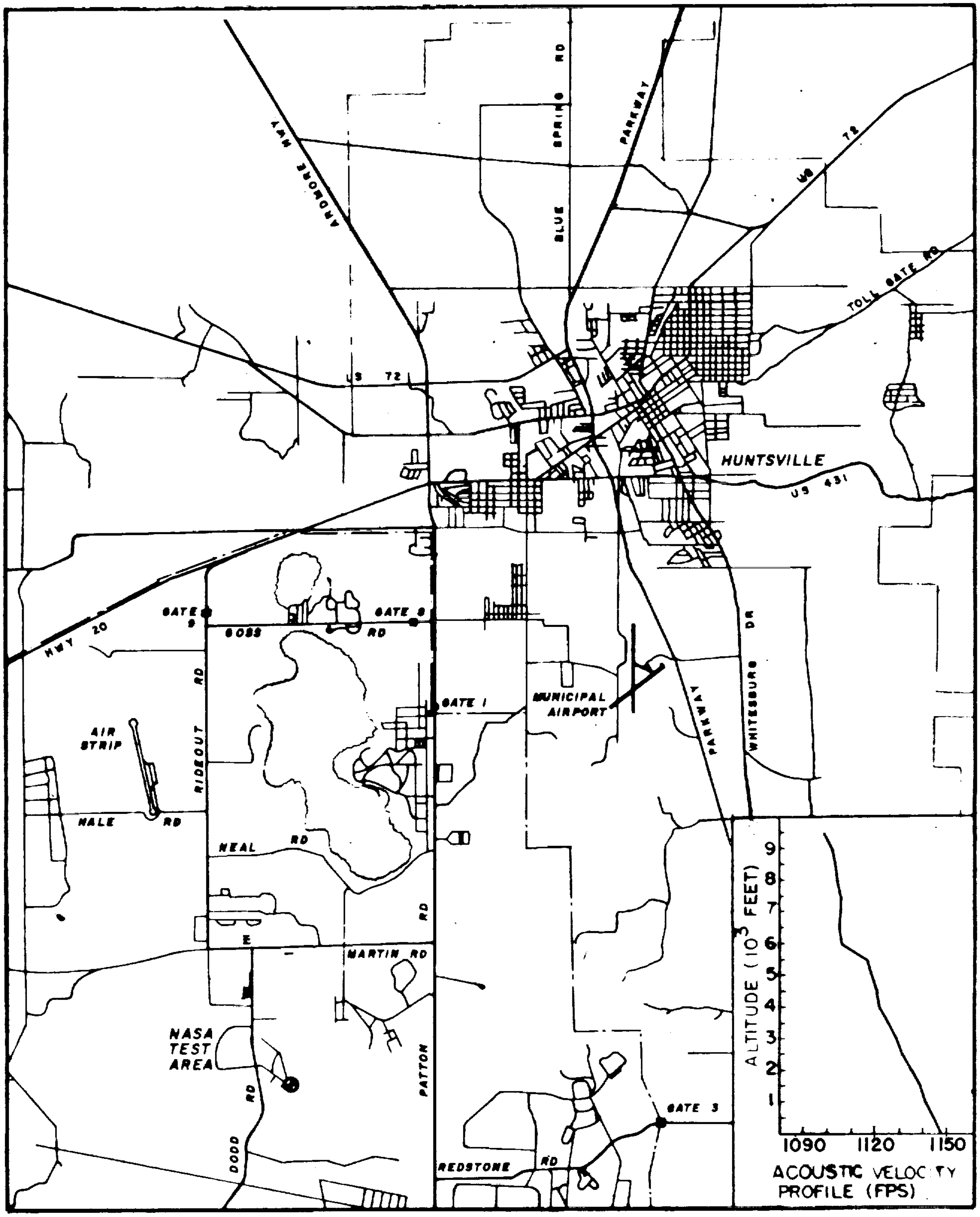


FIGURE 41. TEST SAT-07, JUNE 8, 1960

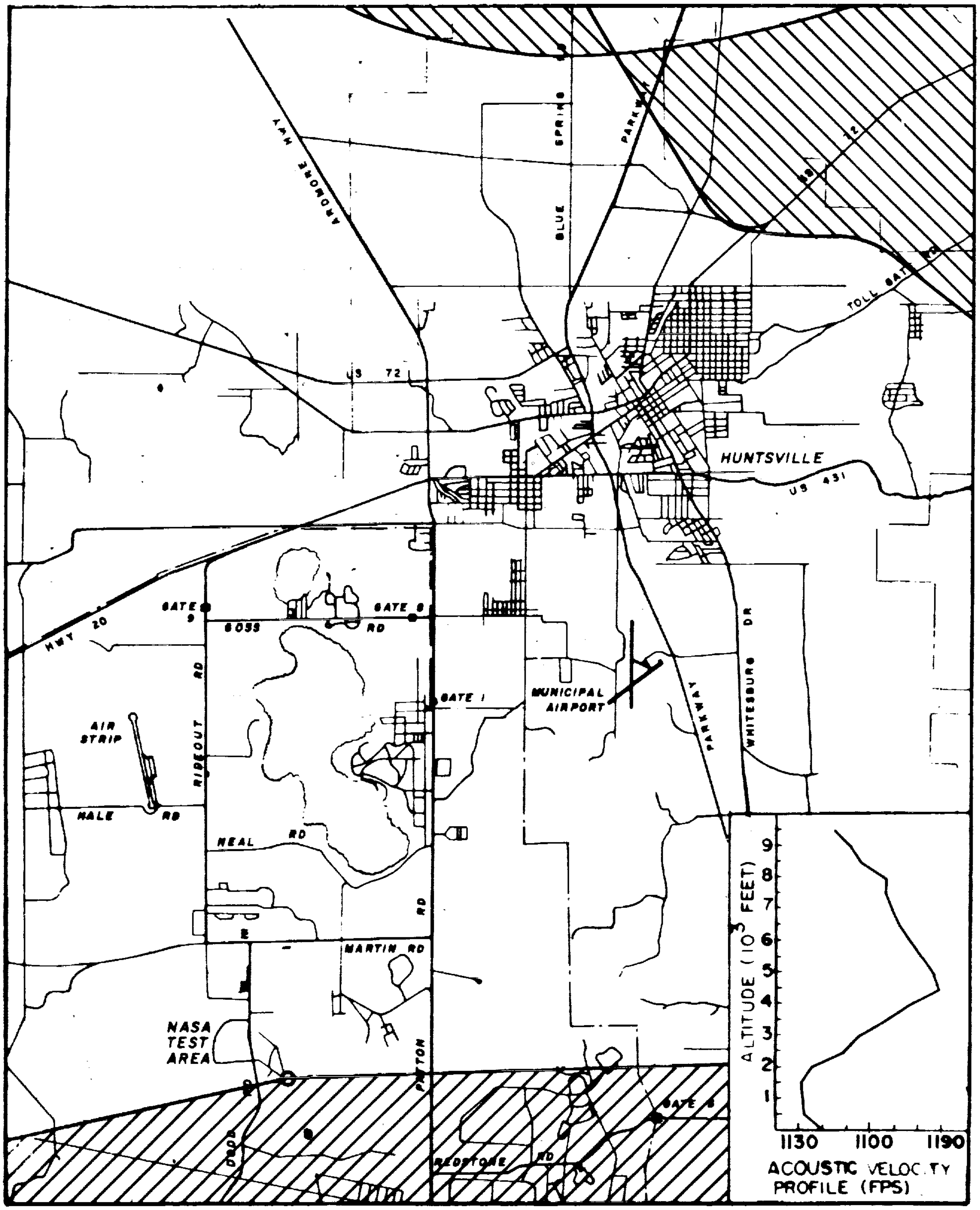


FIGURE 42. TEST SAT-08, JUNE 15, 1960

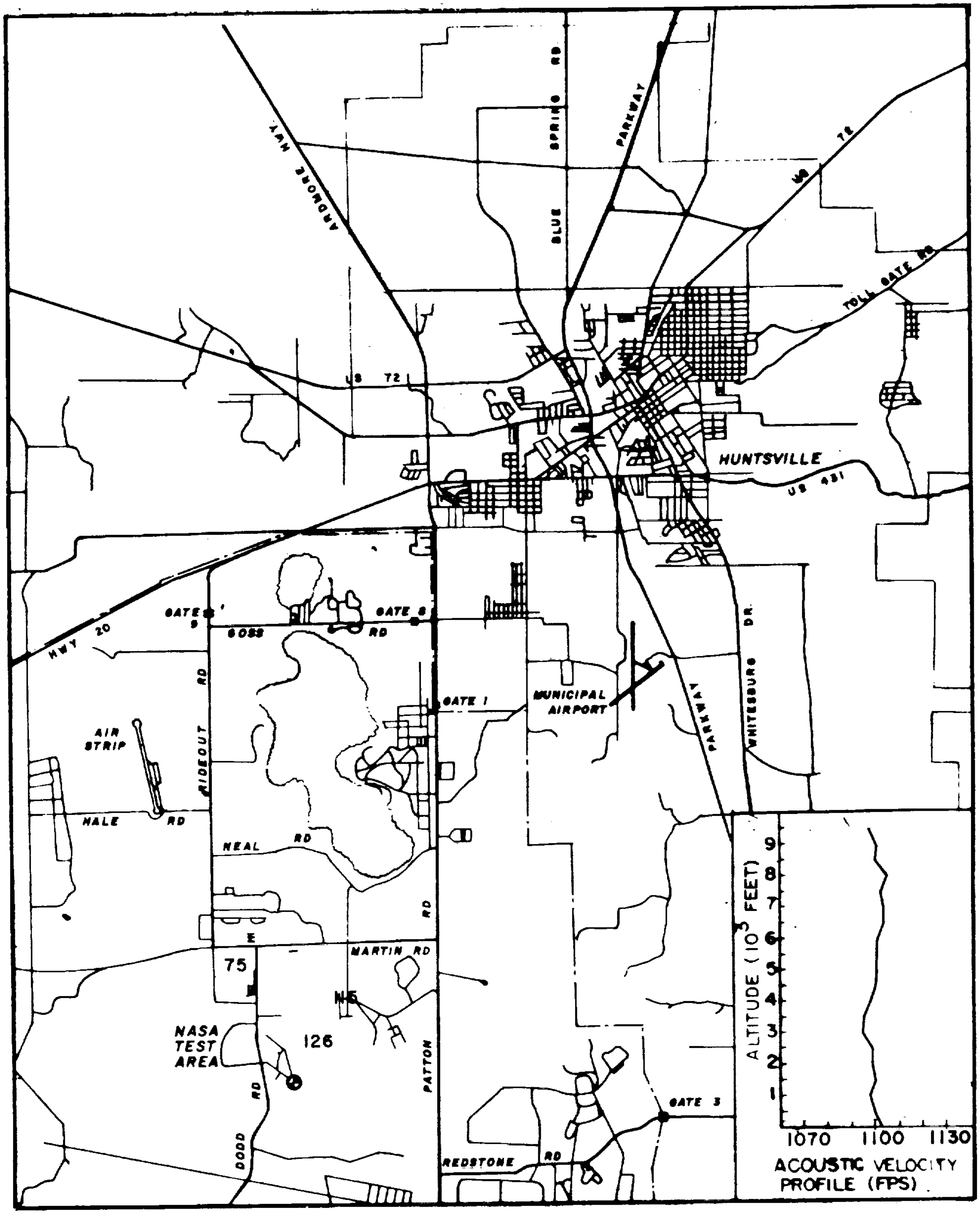


FIGURE 43. TEST SAT-09, DEC. 2, 1960

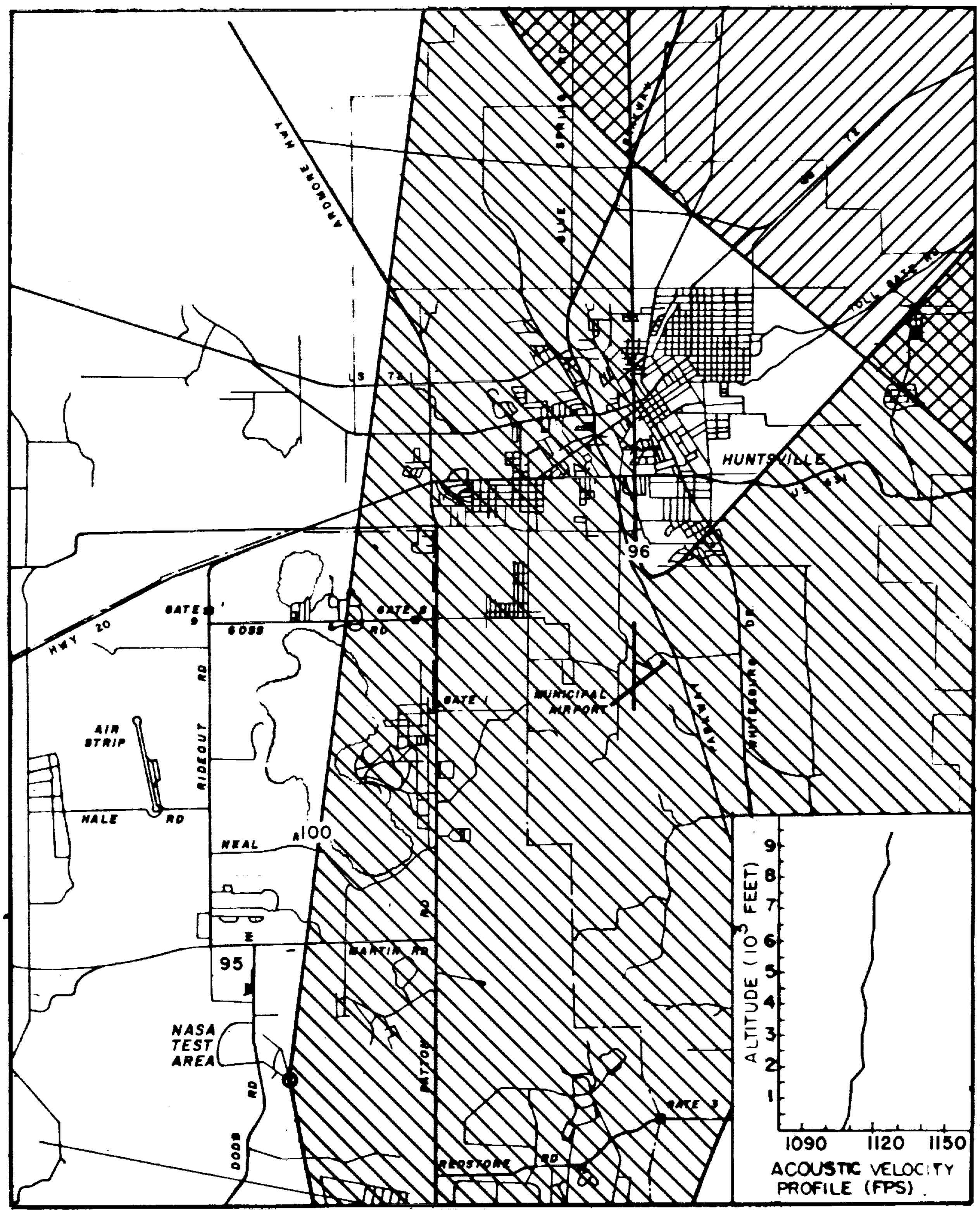


FIGURE 44. TEST SAT-10, Dec.10, 1960

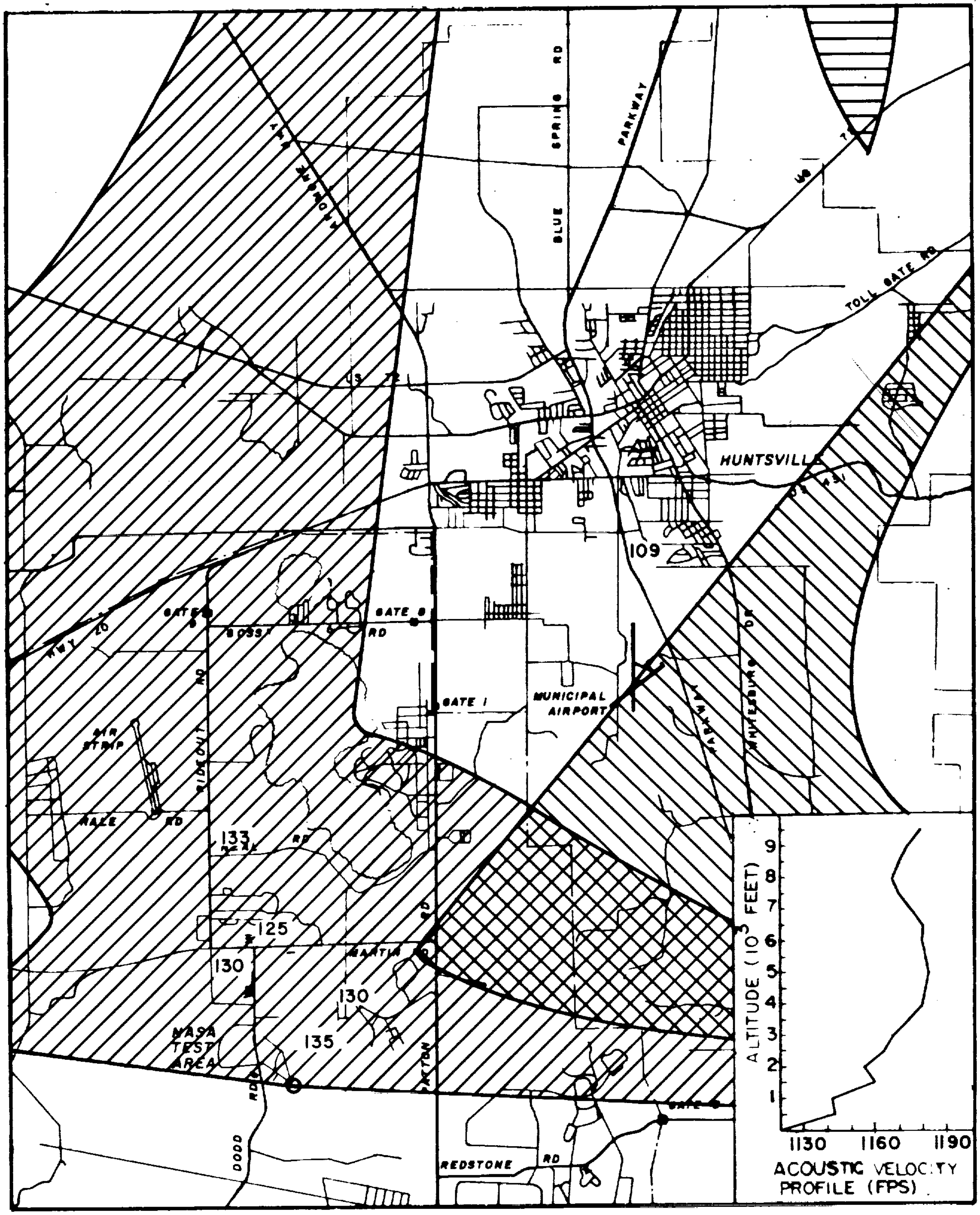


FIGURE 45. TEST SAT-11, DEC. 20, 1960

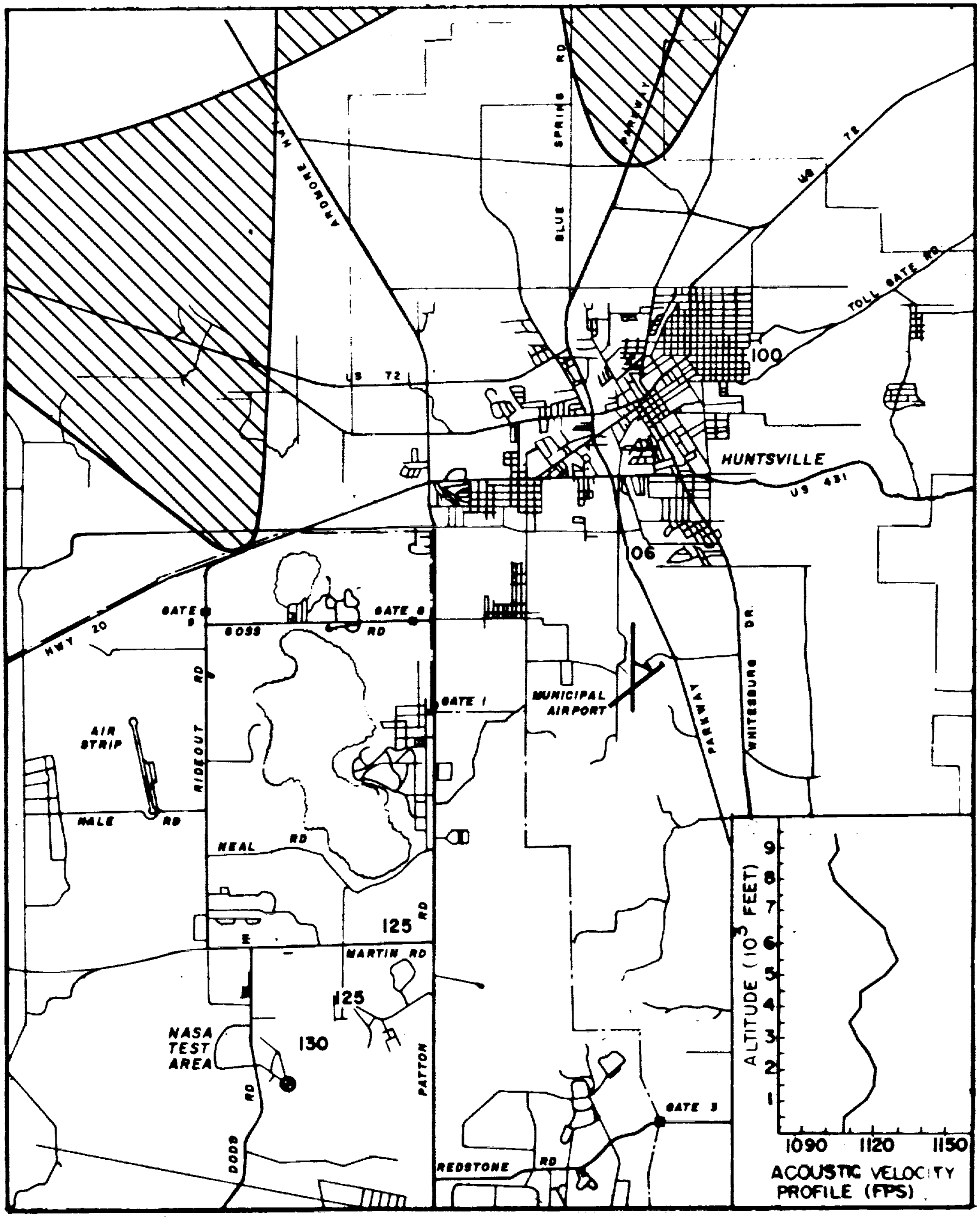


FIGURE 46. TEST SAT-12, JAN. 31, 1961

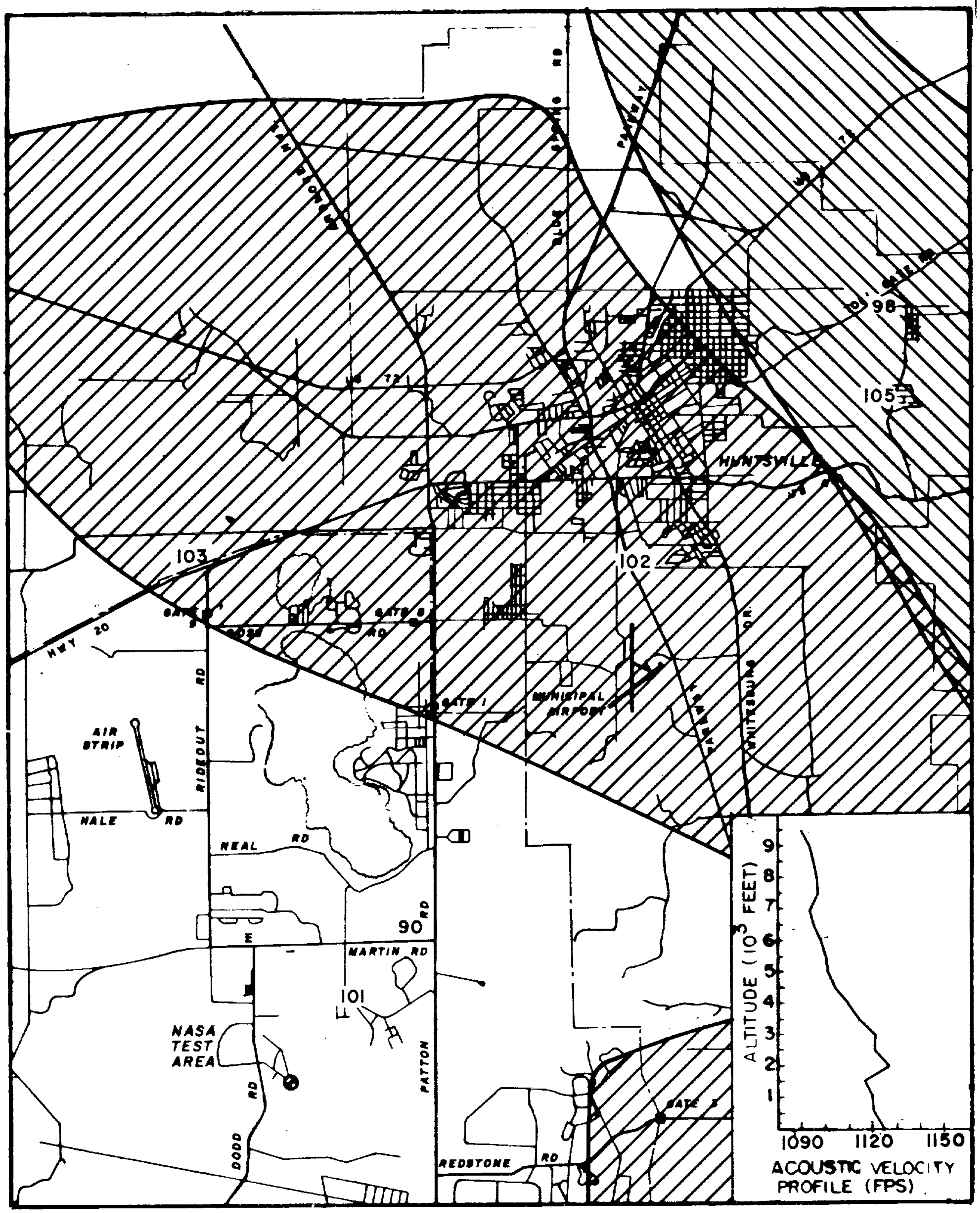


FIGURE 47. TEST SAT-13, FEB. 14, 1961

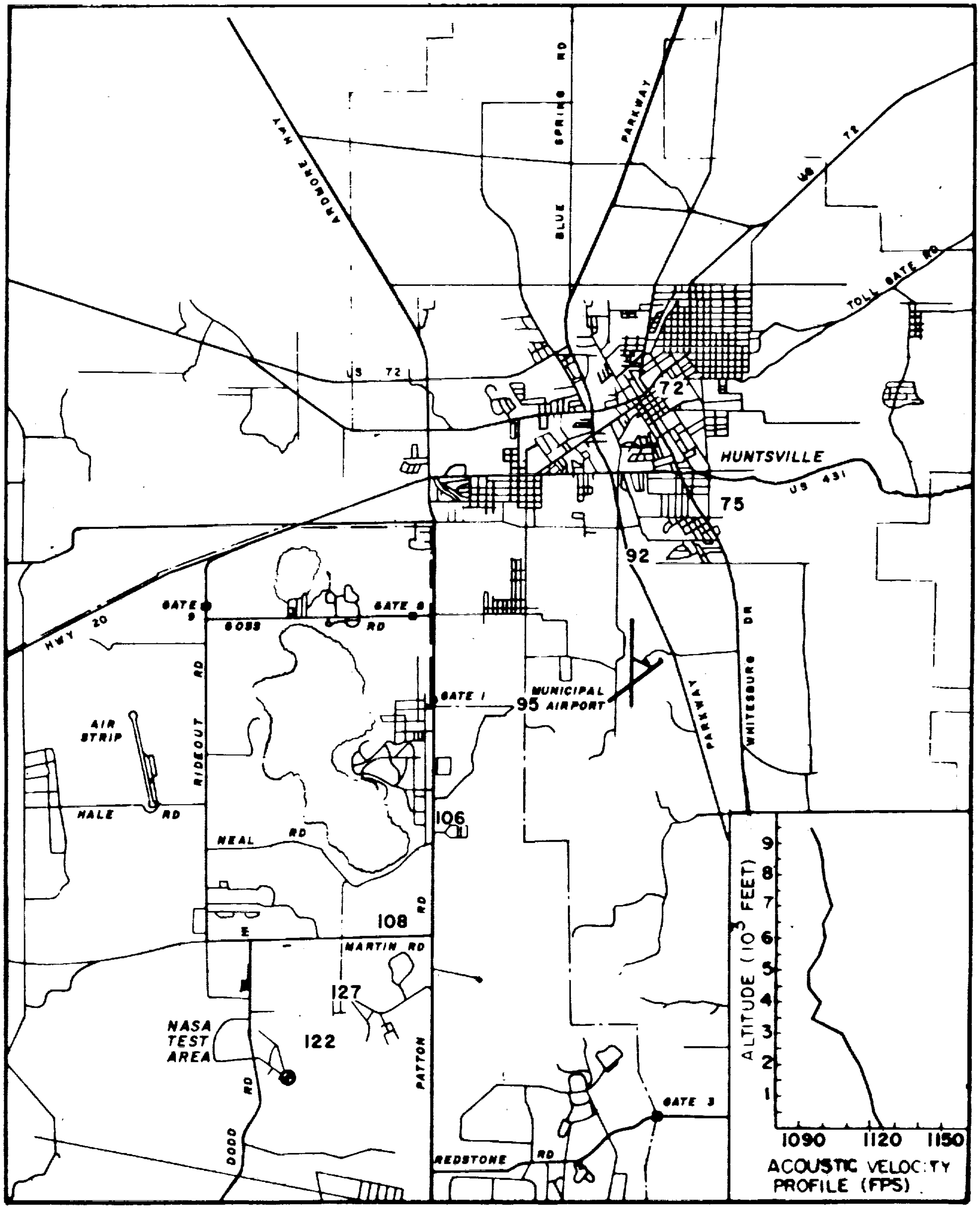


FIGURE 48. TEST SA-01, APRIL 29, 1961

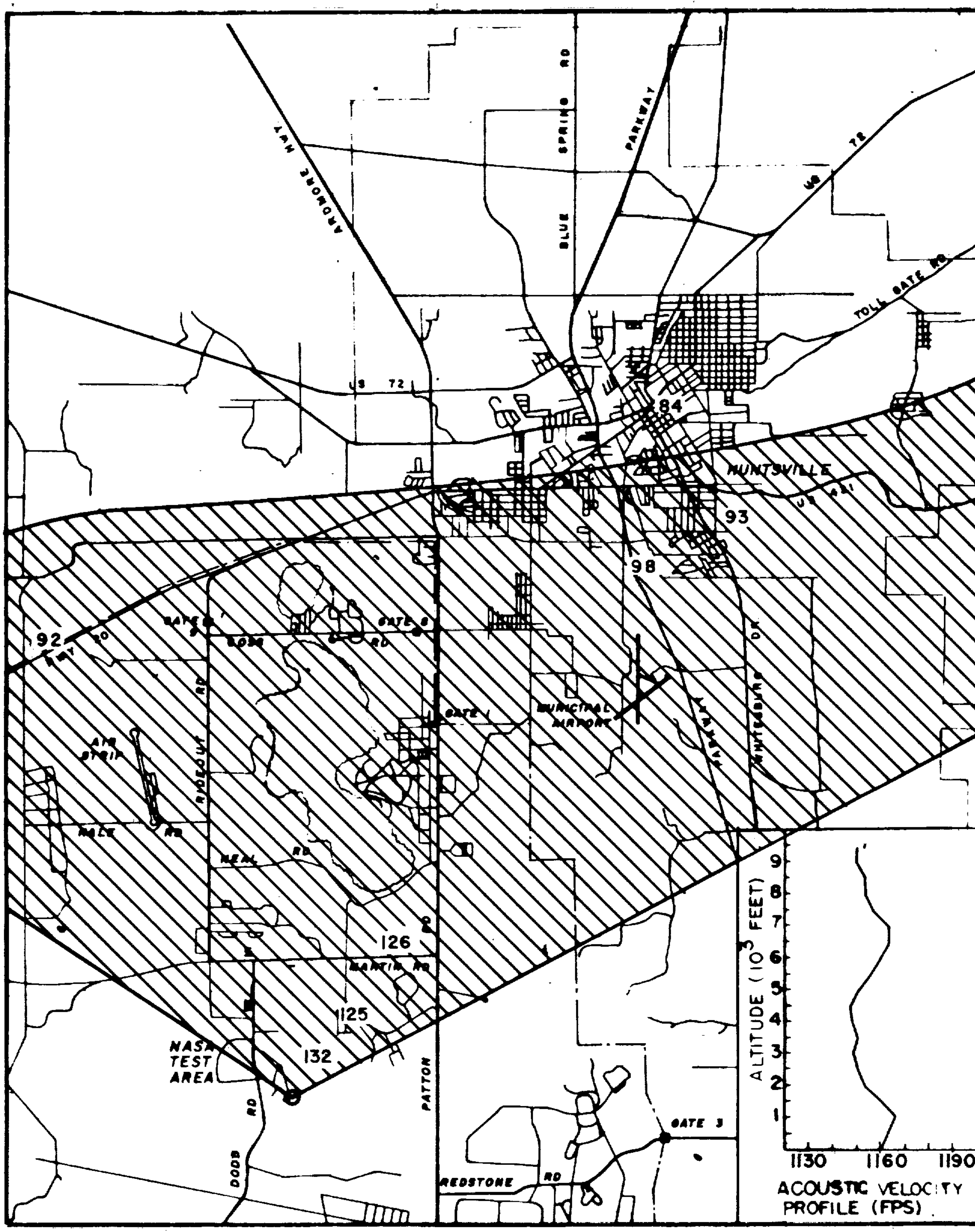


FIGURE 49. TEST SA-02, MAY 5, 1961

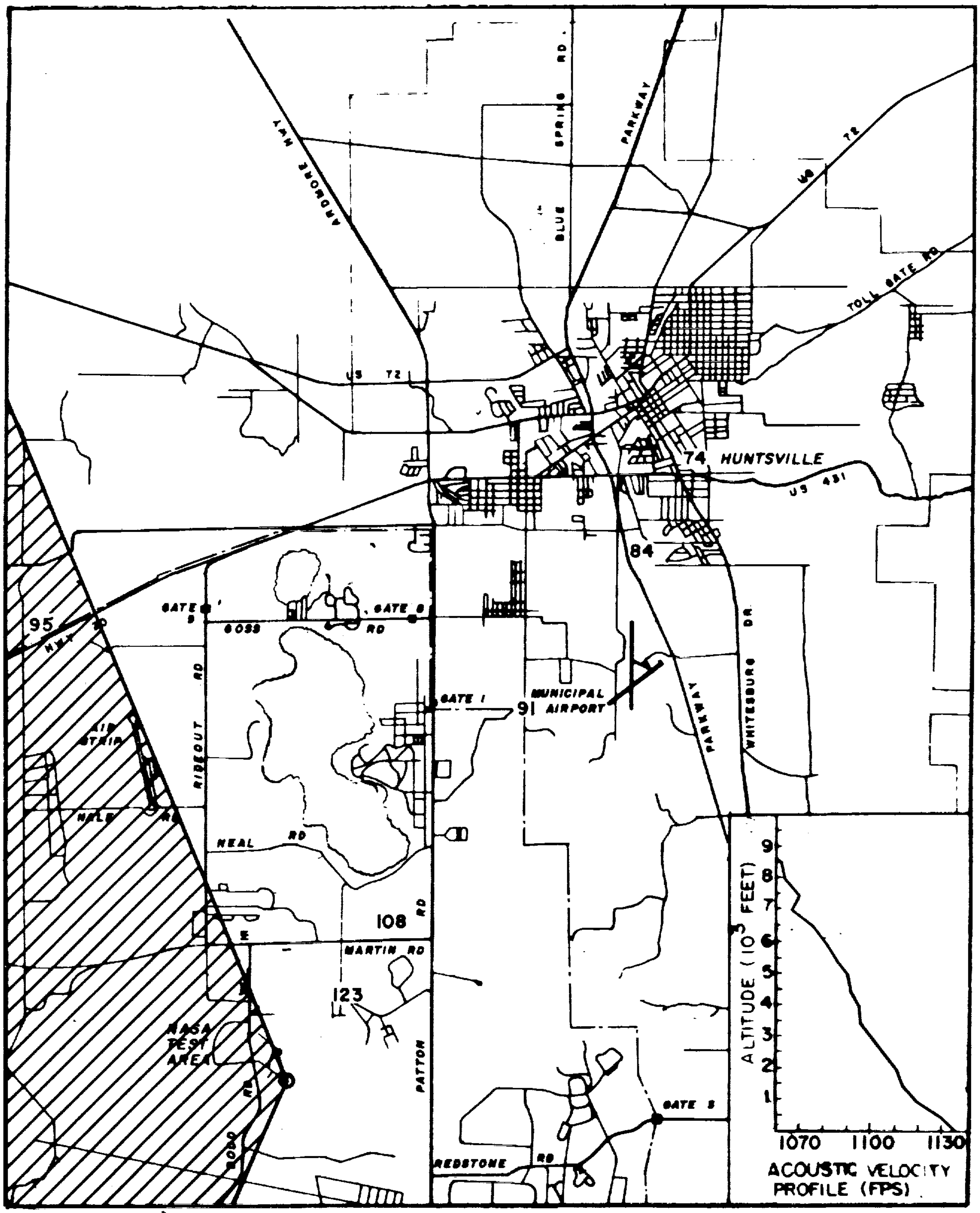


FIGURE 50. TEST SA-03, MAY 11, 1961

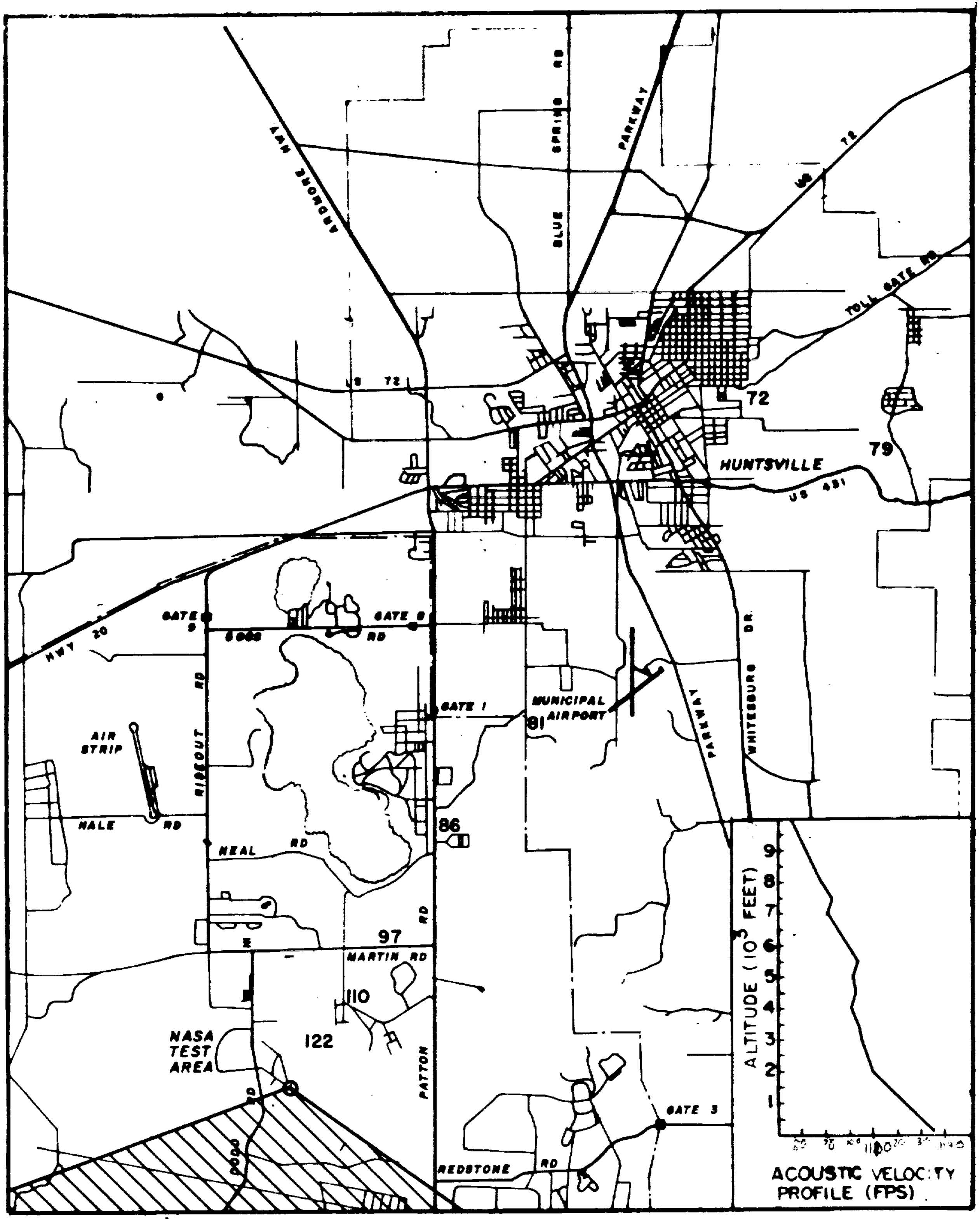


FIGURE 51. TEST SAT-14, JUNE 27, 1961

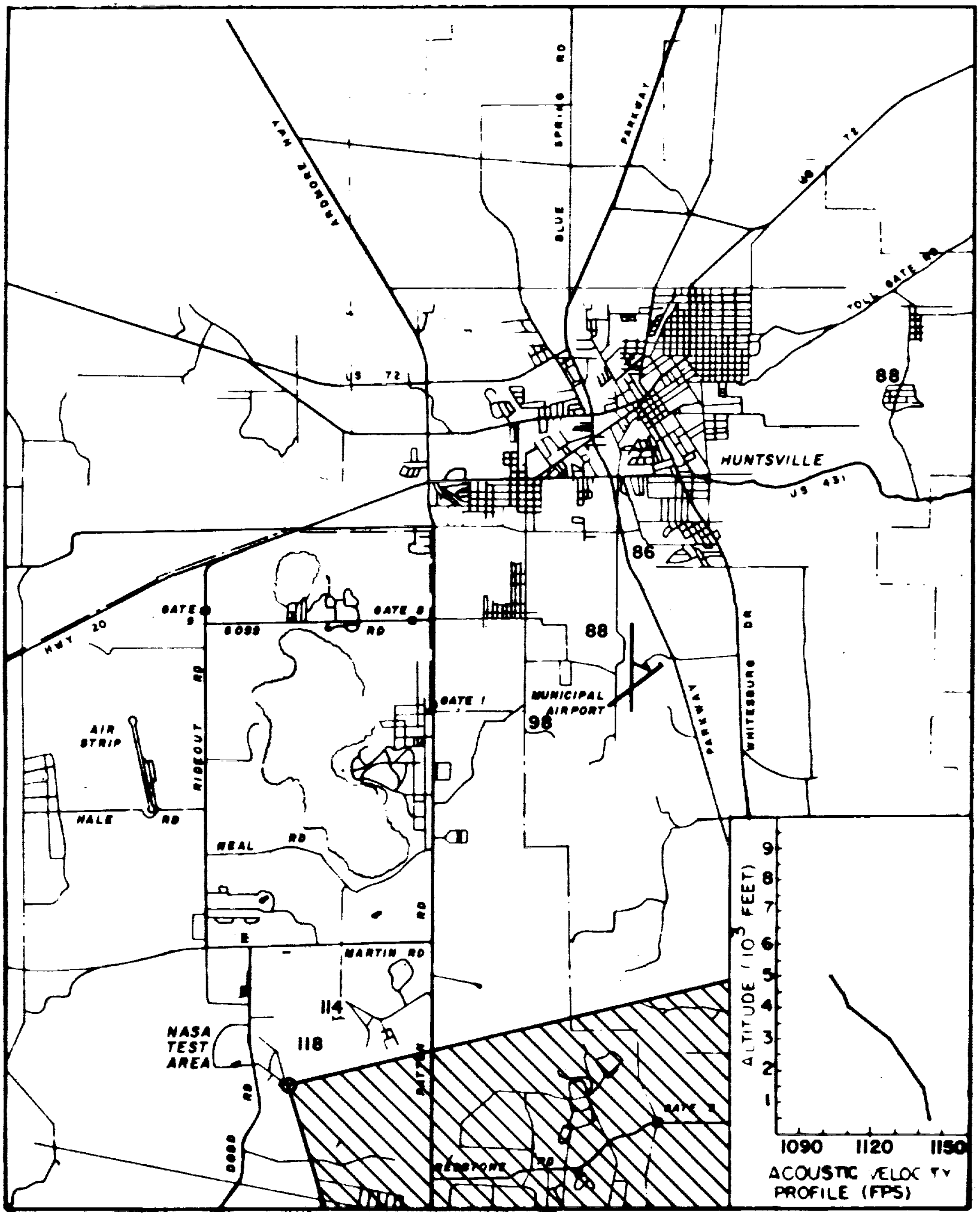


Figure 52 Test Sat-15 July 7, 1961

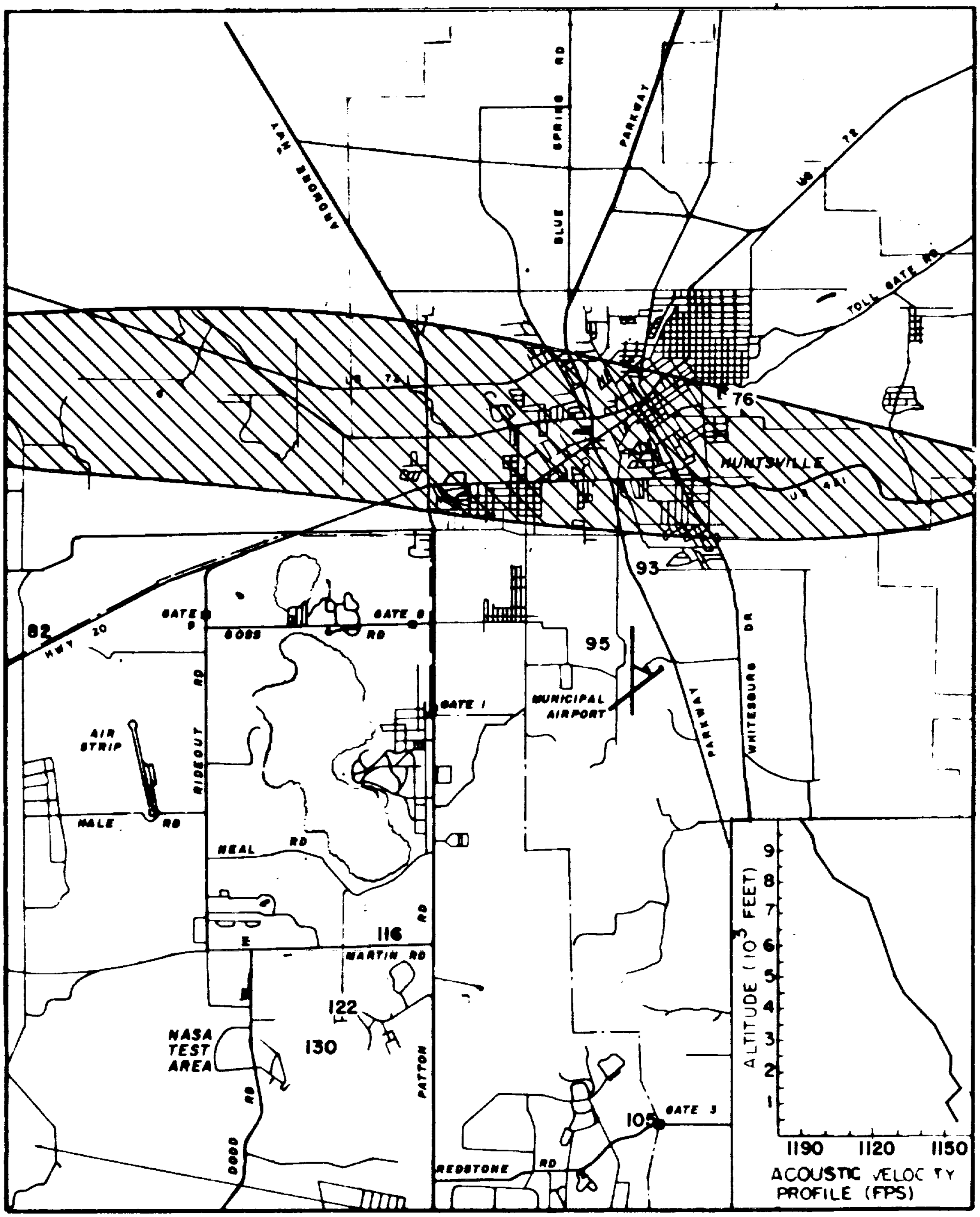


FIGURE 53. TEST SAT-16, JULY 18, 1961

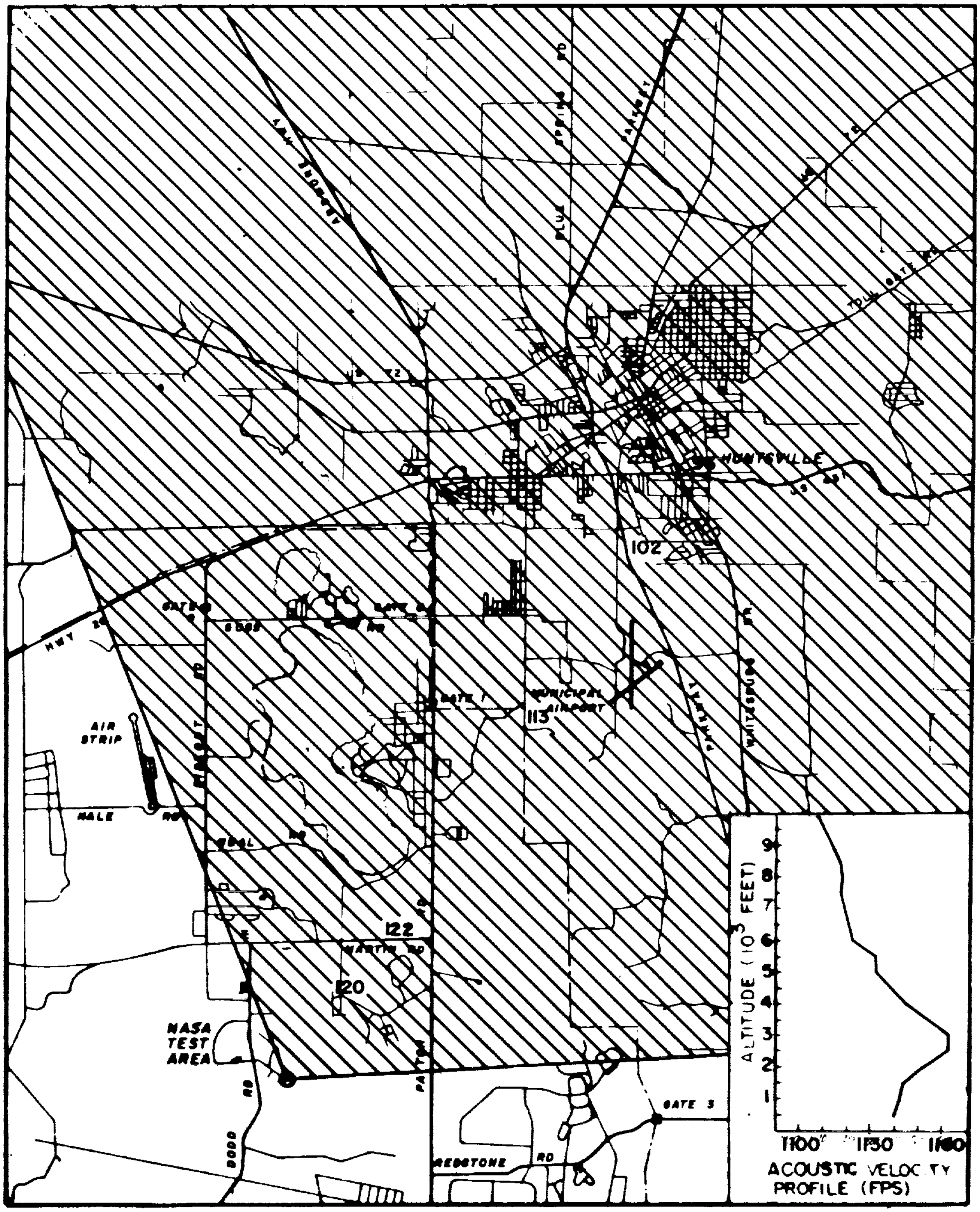


FIGURE 54. TEST SAT-18, AUG. 7, 1961

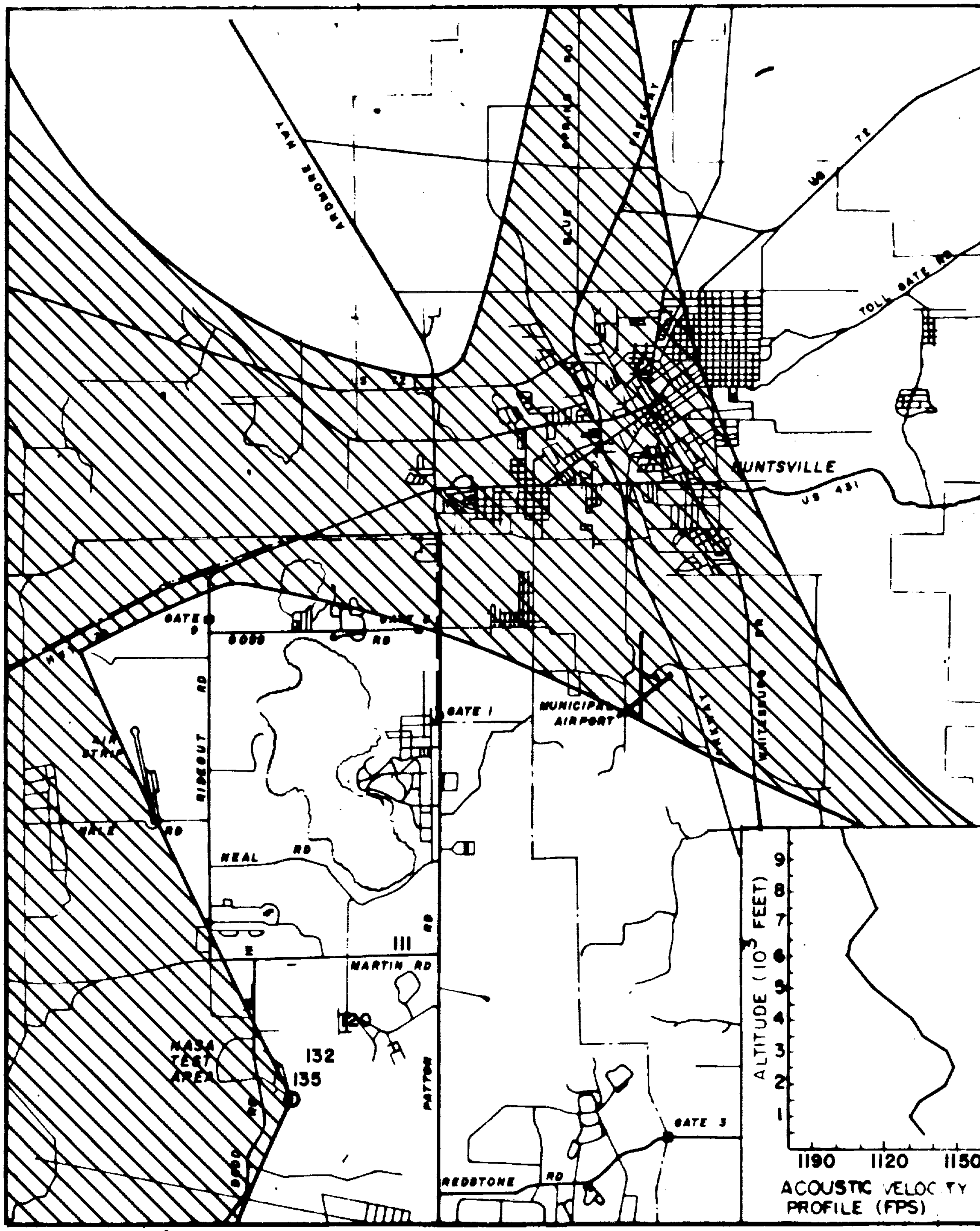


FIGURE 55. TEST SAT-19, AUG. 25, 1961

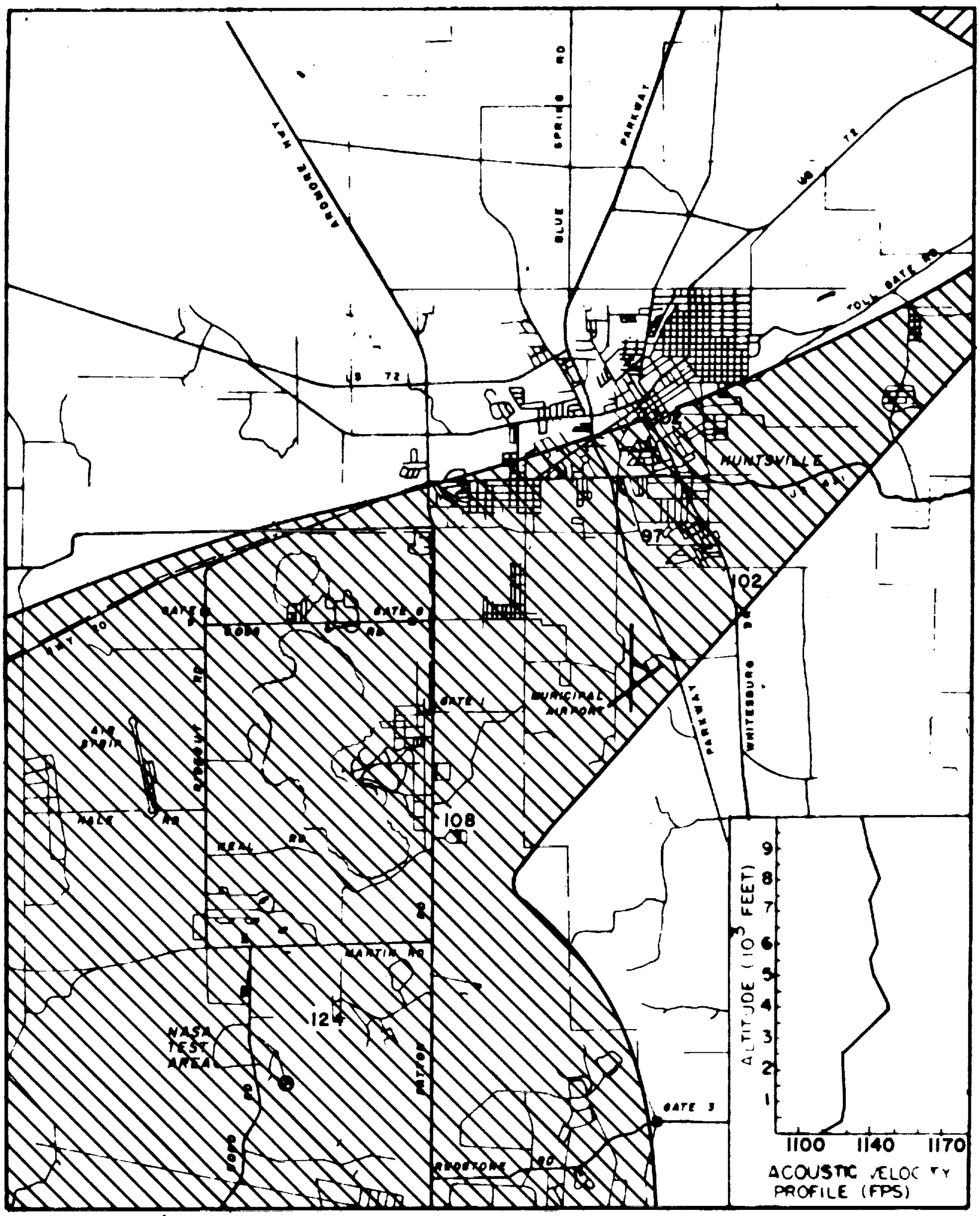


FIGURE 56. TEST SAT-20, NOV. 30, 1961

As can be seen from an examination of these figures, the measurements generally agree with the calculated focal areas. The boundaries appear to be fairly well defined but are subject to some shadow zone diffusion. This diffusion may be explained by Huygen's principle which states that no finite energy wave travelling in an infinite homogeneous medium may travel in only one direction since each point on the wave front acts as a new point source. Consequently, there would be some energy "spill-out" into any shadow zone.

The far-field measurements are shown again in FIGURES 57 through 70. Included for reference in these figures are the curves for inverse square law attenuation and the attenuation due to humidity and molecular absorption (Ref. 24). The latter attenuation curve was based rather arbitrarily upon a loss of 4db SPL per mile. However, it can be seen that this particular loss figure is quite weather dependent and is subject to some rather rapid changes upon entering focal zones. The acoustic source was the eight-engine Saturn C-1 configuration which had a nominal thrust of 1.3 million pounds and an acoustic efficiency of approximately 0.5 percent. SAT-10 was only a two engine test.

It would appear from consideration of the empirical sound pressure level data that one or more focal areas is the shift upward of the whole SPL curve a certain number of decibels. It appears also that the shifts are additive, resulting in an apparent rise in the sound pressure level of the source.

The focal conditions noted resulted in appropriate rises in measured sound pressure levels. However, during test SAT-12, an abrupt rise was noted at approximately two miles from the source, in an area where no such focus was anticipated. One possible explanation of such an occurrence lies in the manner in which the meteorological data are reduced. The data were provided at fixed 500-foot altitude increments because of the requirements of other projects utilizing the data. If the maxima and minima of the velocity profile do not appear at those precise altitude levels, then they are, to all extents, lost and only the larger trends become discernible. Normally, since the most violent of these local inhomogeneities occur near the surface, their results could be expected to become evident within the first few miles.

Thus, if somewhere between the 1000 and 1500 feet altitude boundaries there existed a layer which contained a wind only five to seven miles per hour higher than that measured at the 1500 foot layer boundary, the boundary of the calculated focal area would have been several miles nearer that shown in FIGURE 46. Such an occurrence may be strongly suspected from the levels measured. The above gap in the data might have been resolved if the meteorological parameters had been reported in what the U. S. Weather Bureau calls "significant levels", i.e., important local maxima and minima.

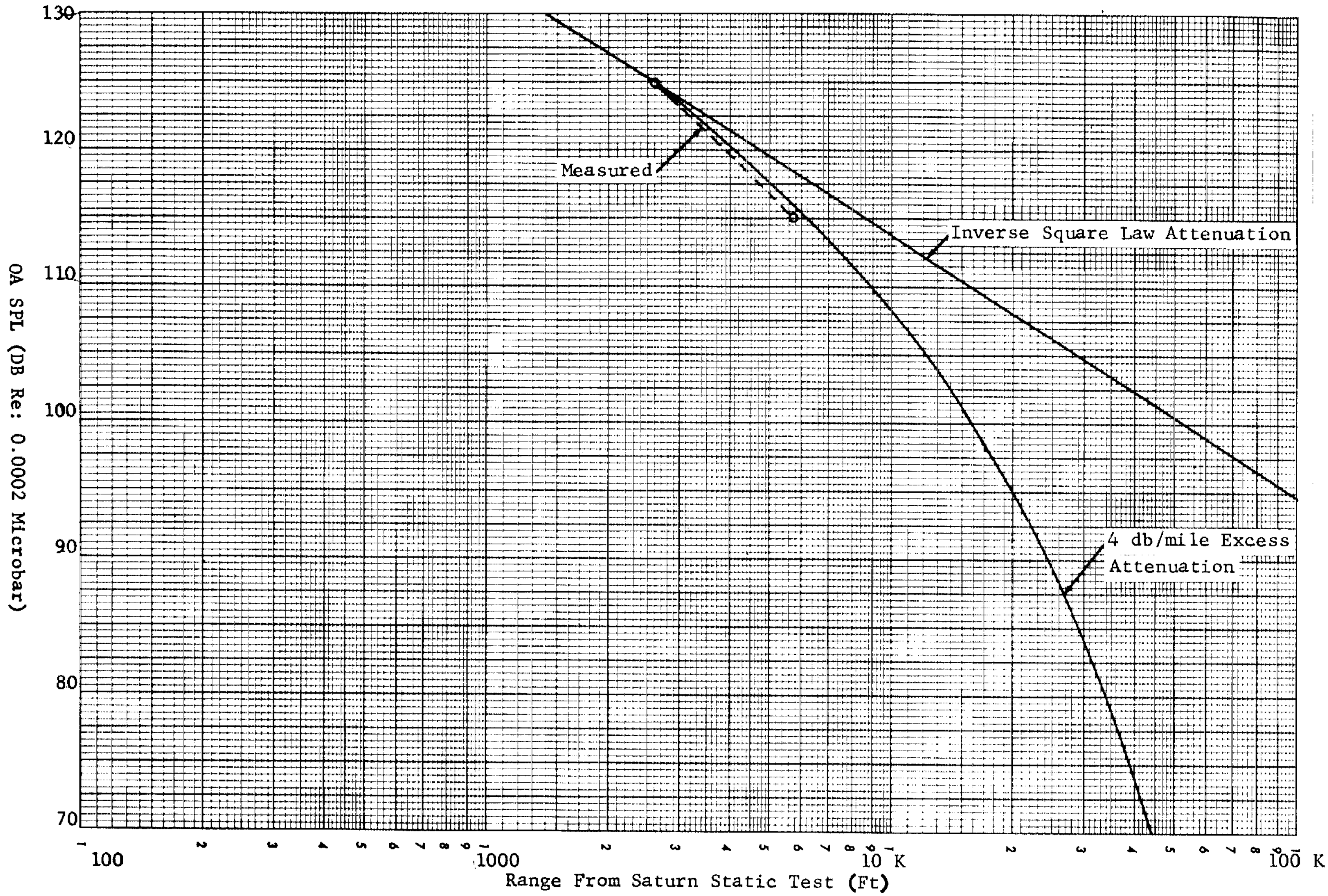


FIGURE 57. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-09 DATE: Dec 2, 1960

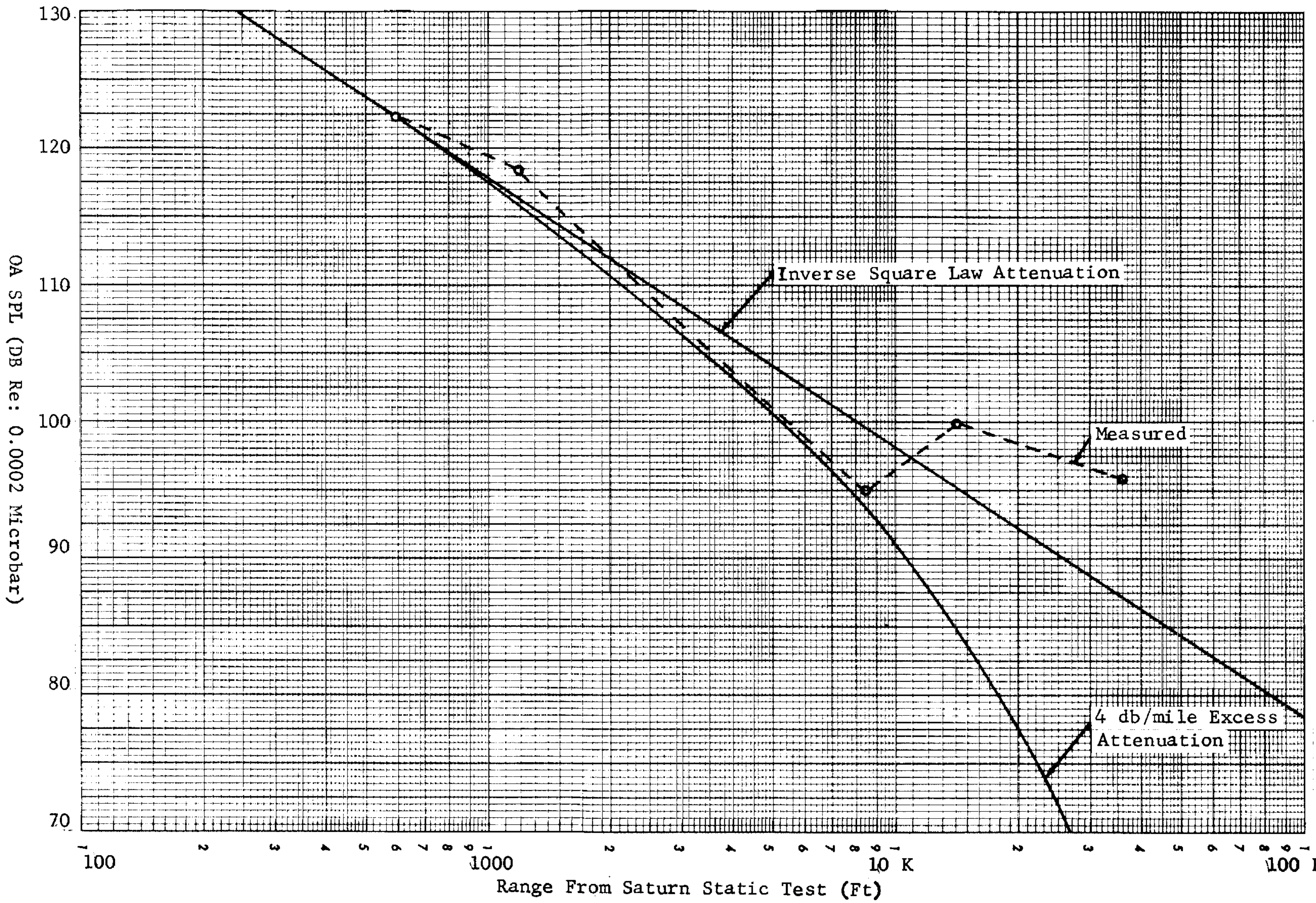


FIGURE 58. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-10 DATE: Dec. 10, 1960

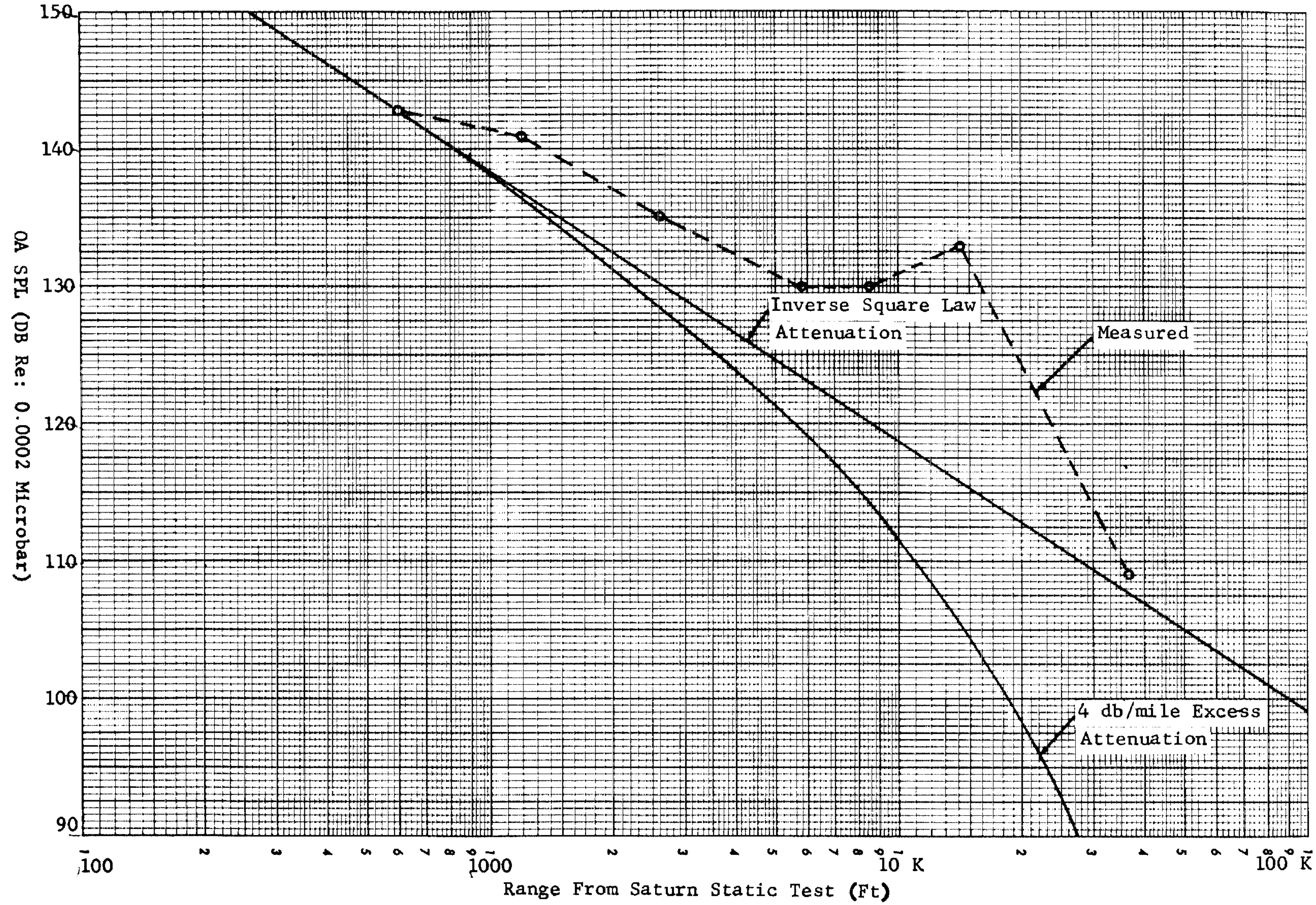


FIGURE 59. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-11 DATE: Dec. 20, 1960

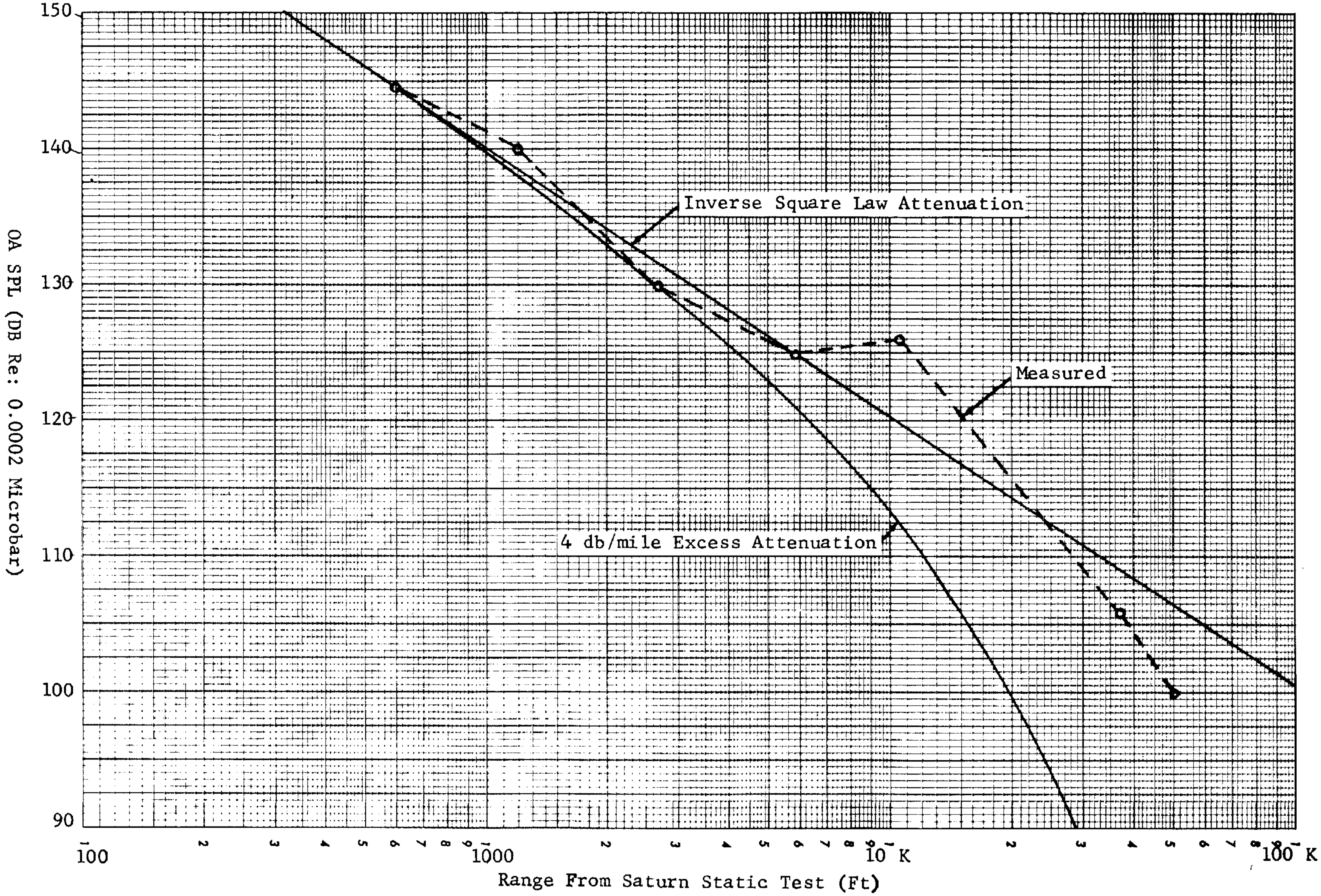


FIGURE 60. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-12 DATE: Jan. 31, 1961

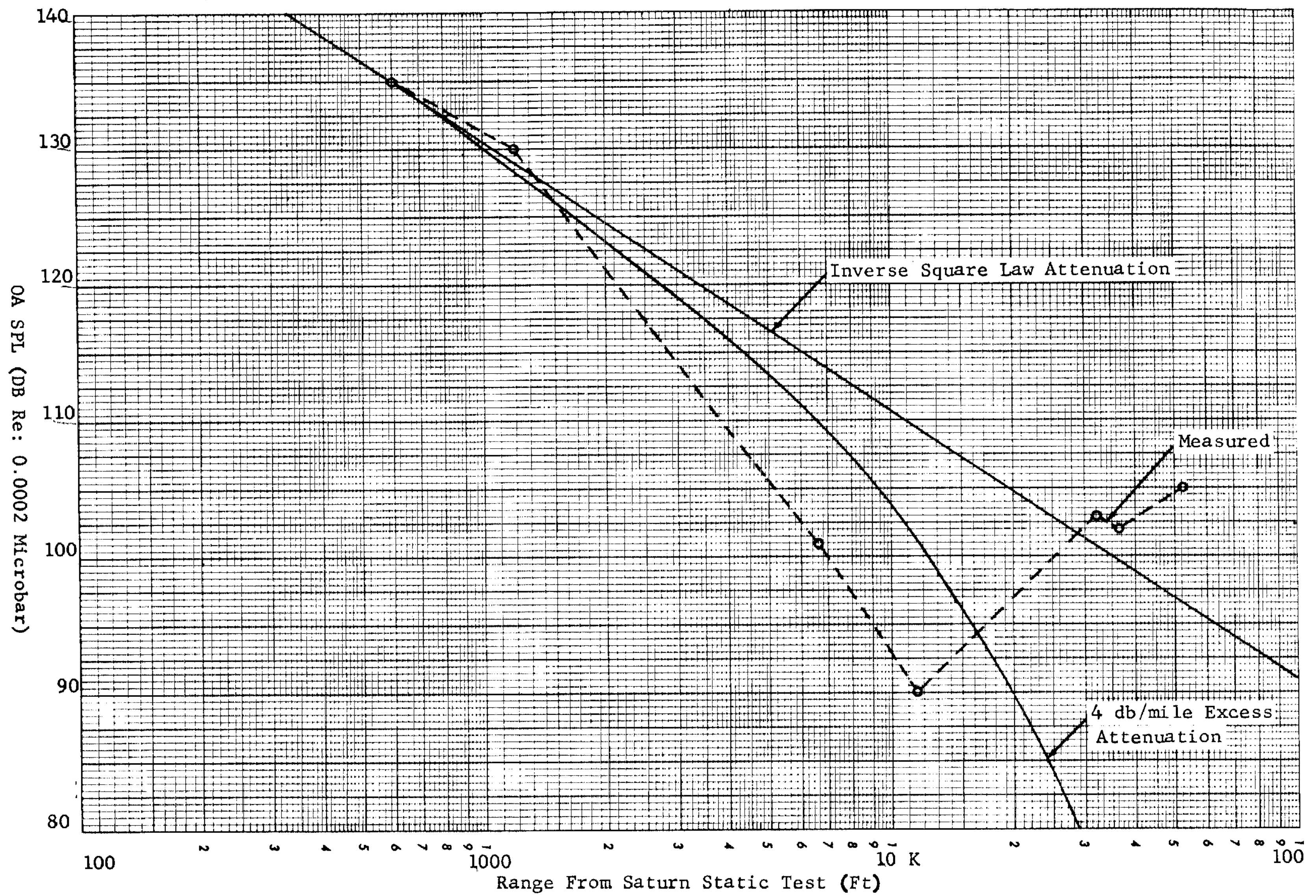


FIGURE 61. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-13 DATE: Feb. 14, 1961

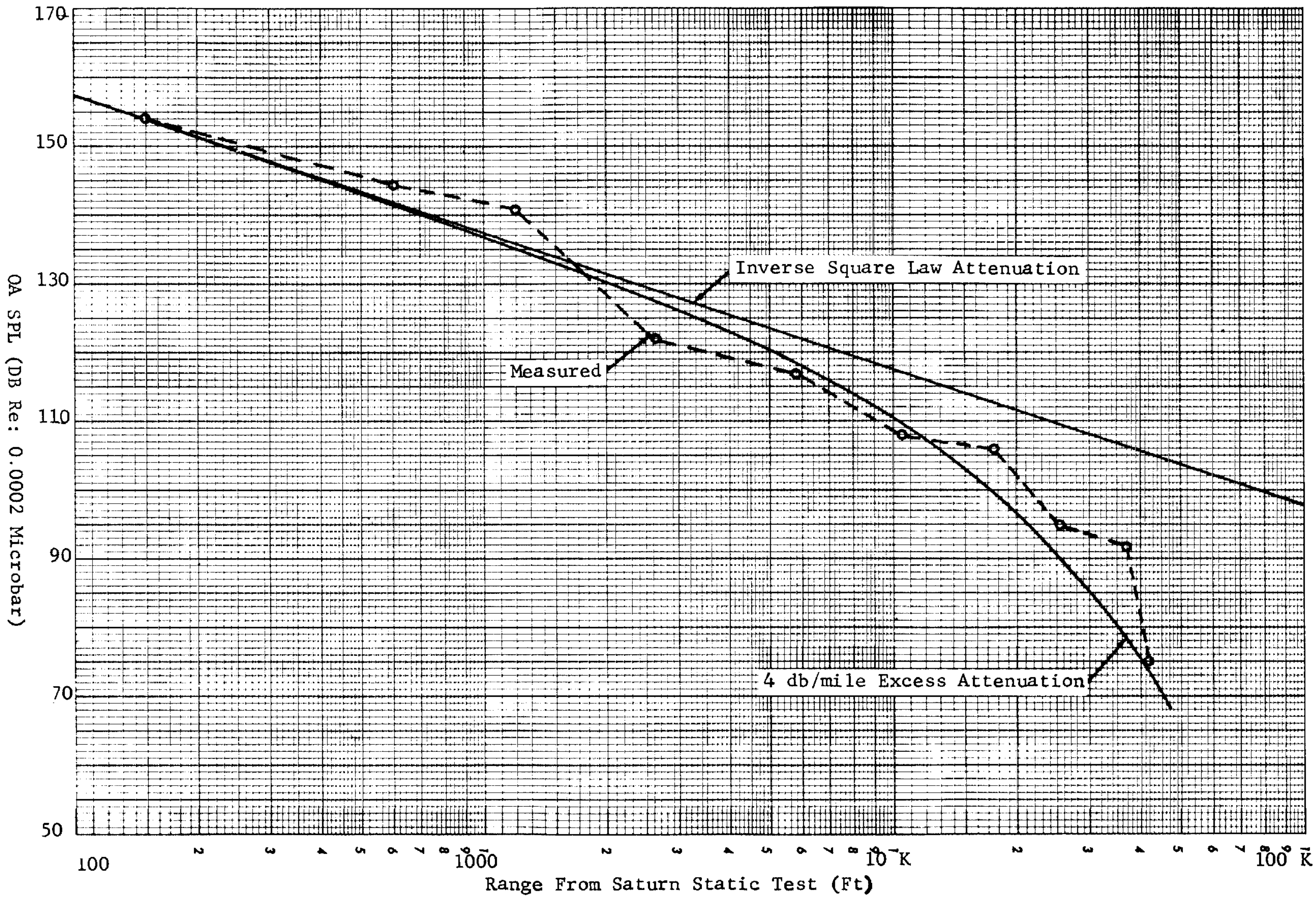


FIGURE 62. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SA-01 DATE: April 29, 1961

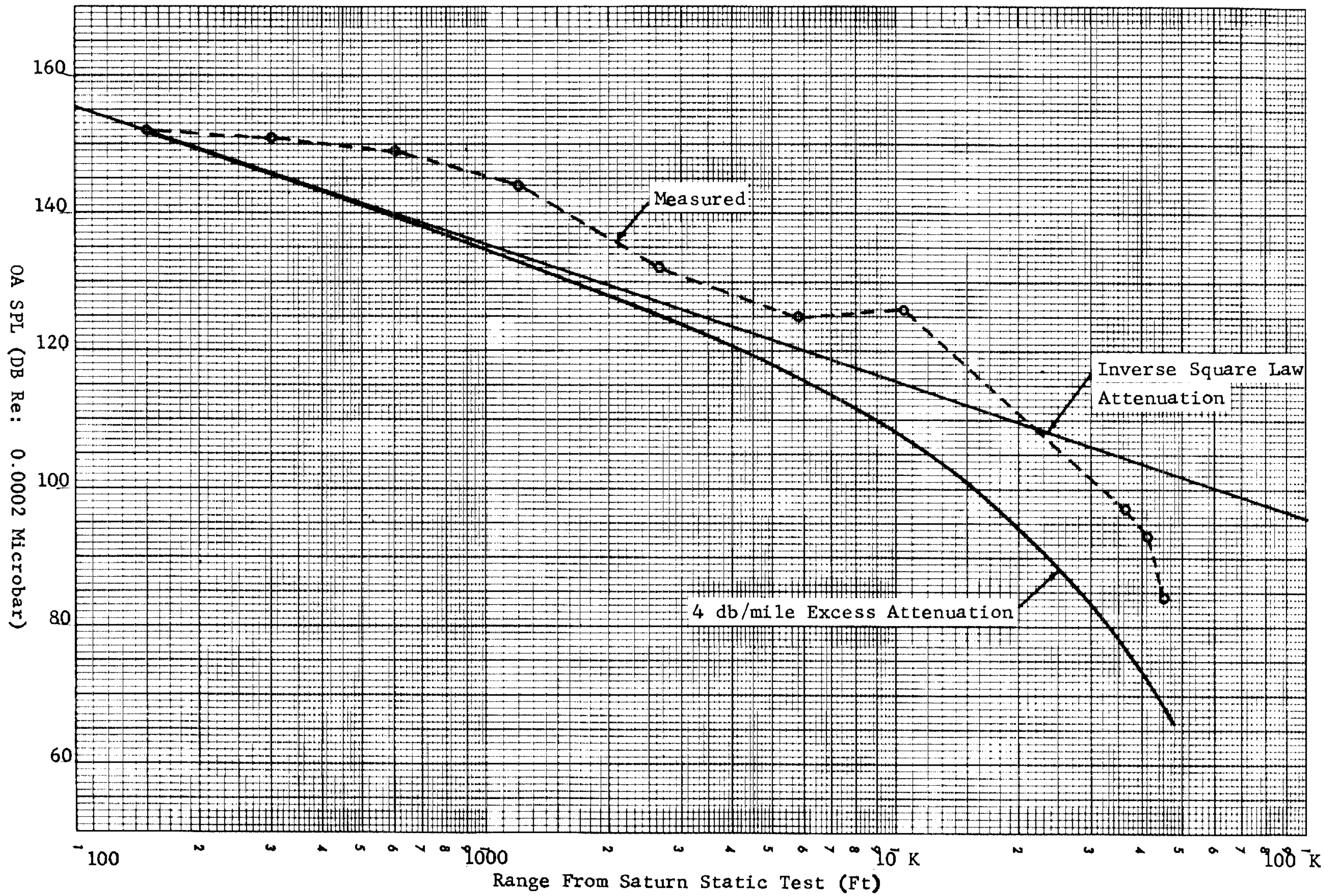


FIGURE 63. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SA-02 DATE: May 5, 1961

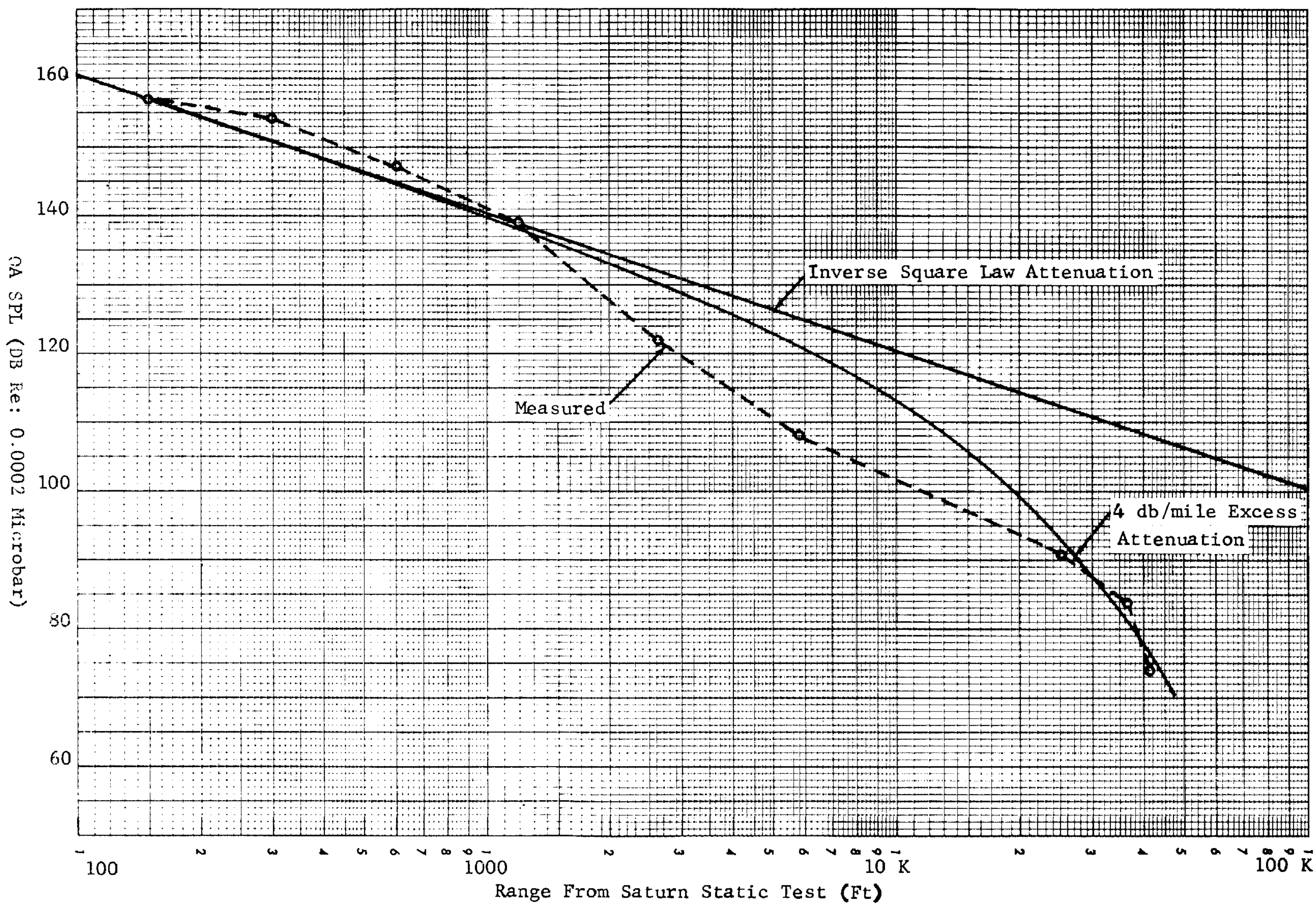


FIGURE 64. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SA-03 DATE: May 11, 1961

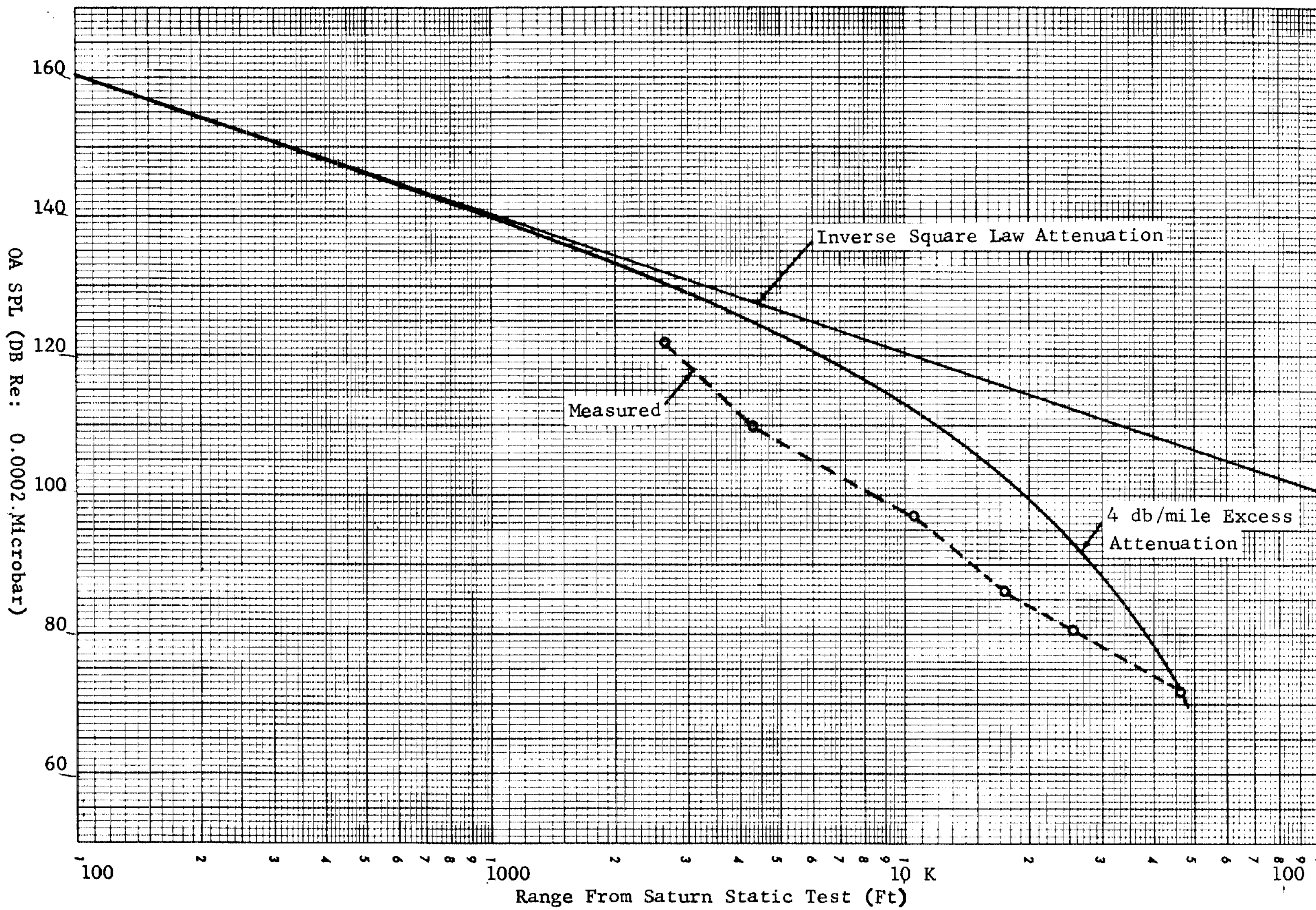


FIGURE 65. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-14

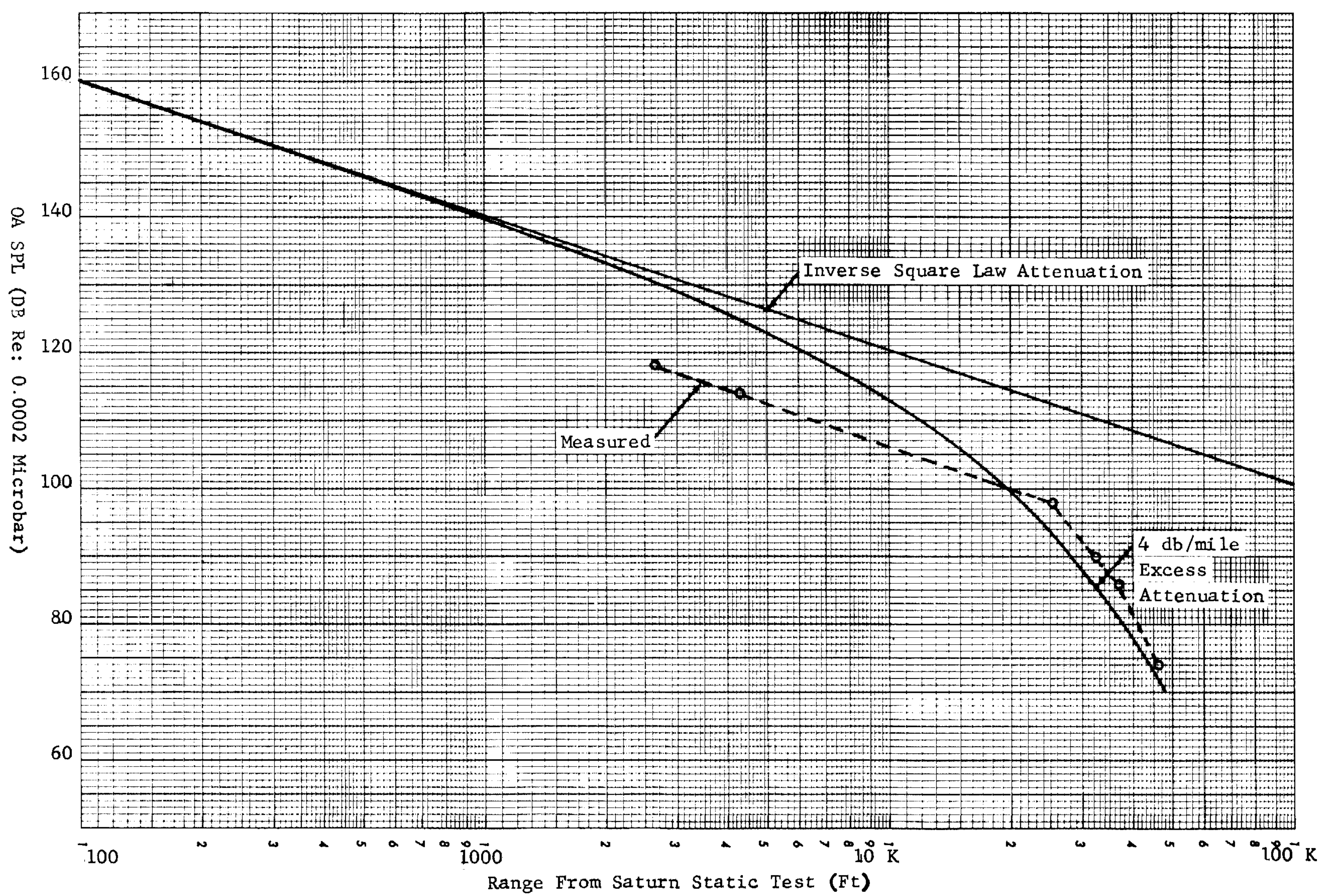


FIGURE 66. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-15

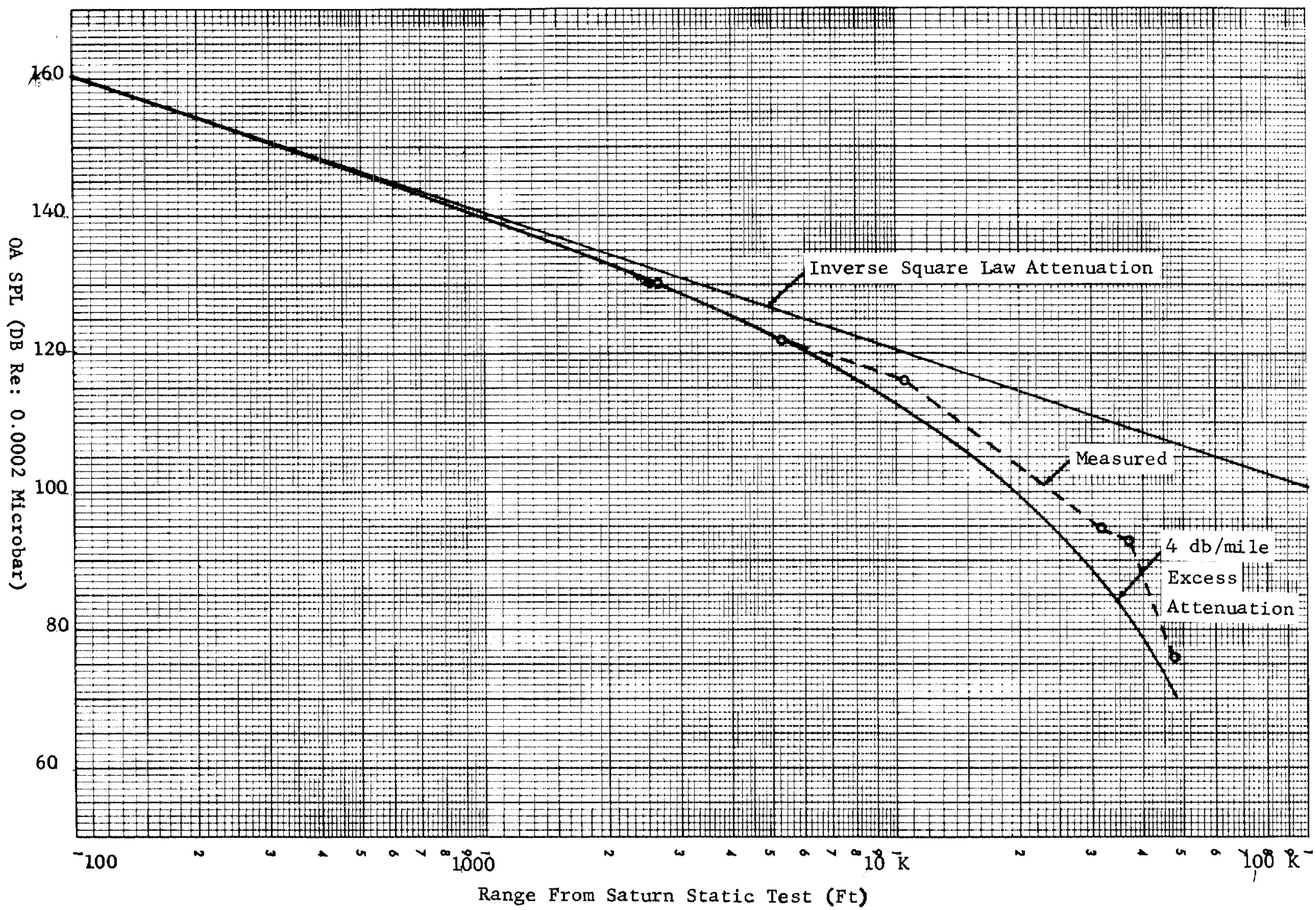


FIGURE 67. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-16

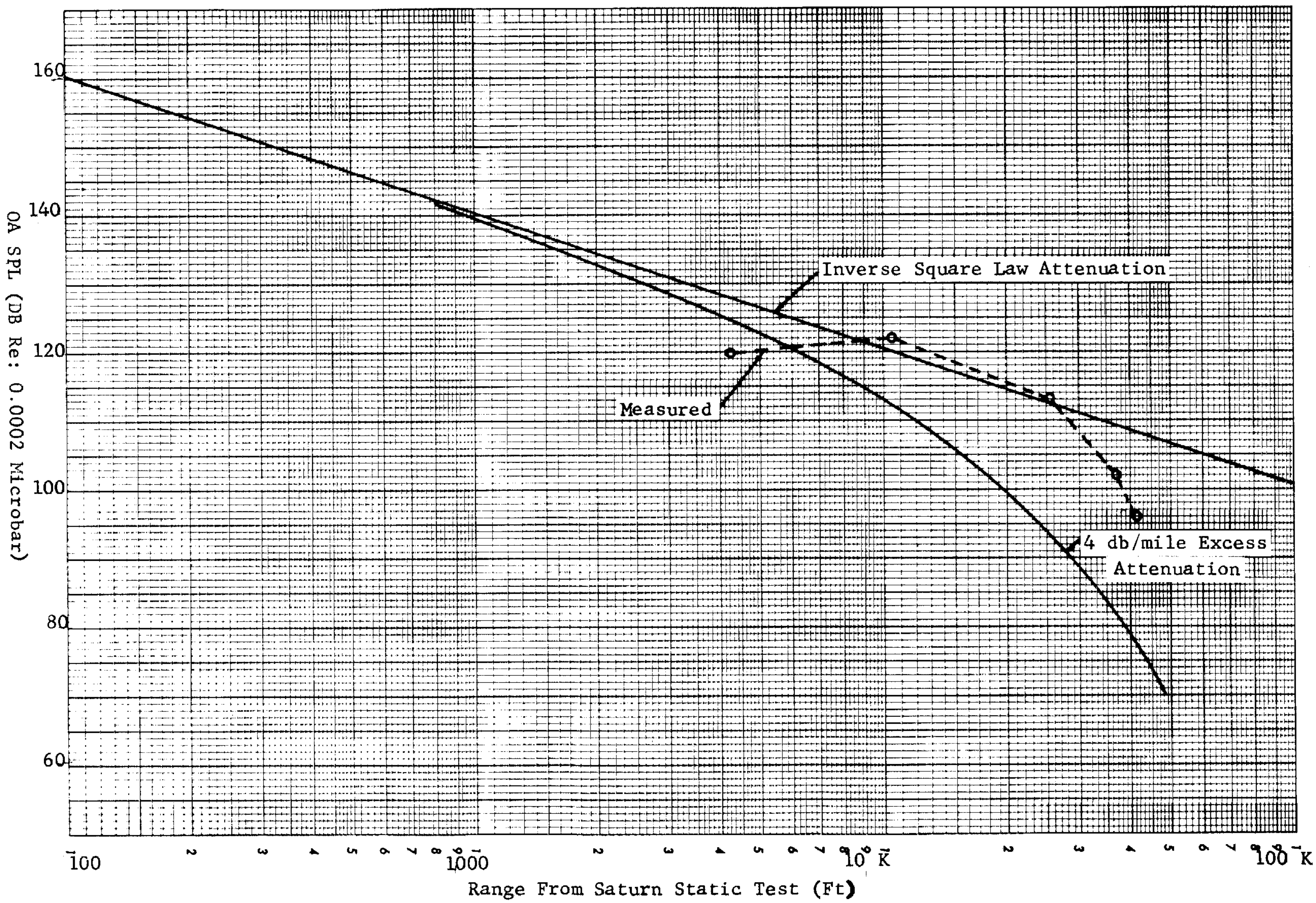


FIGURE 68. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-18

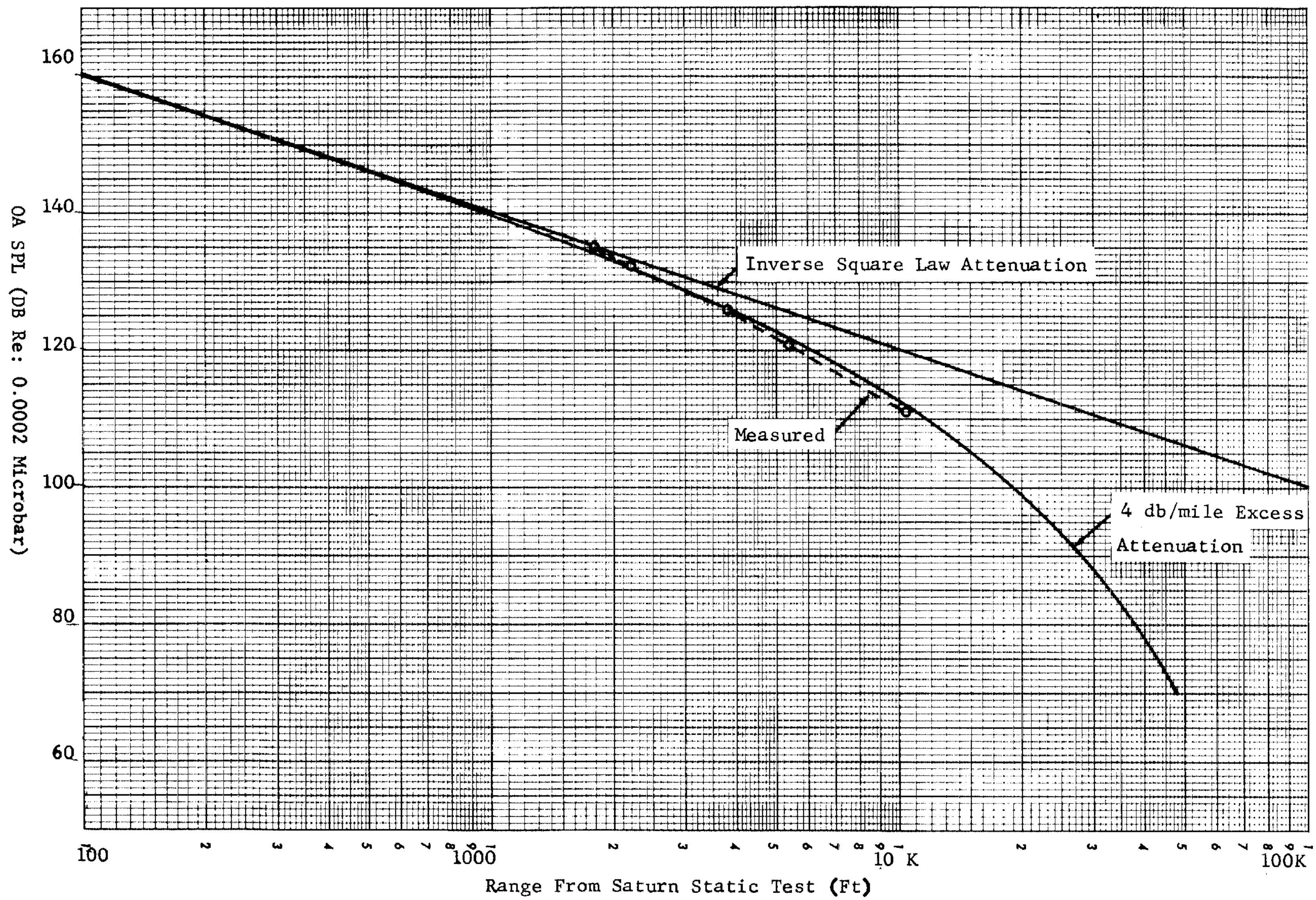


FIGURE 69. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-19

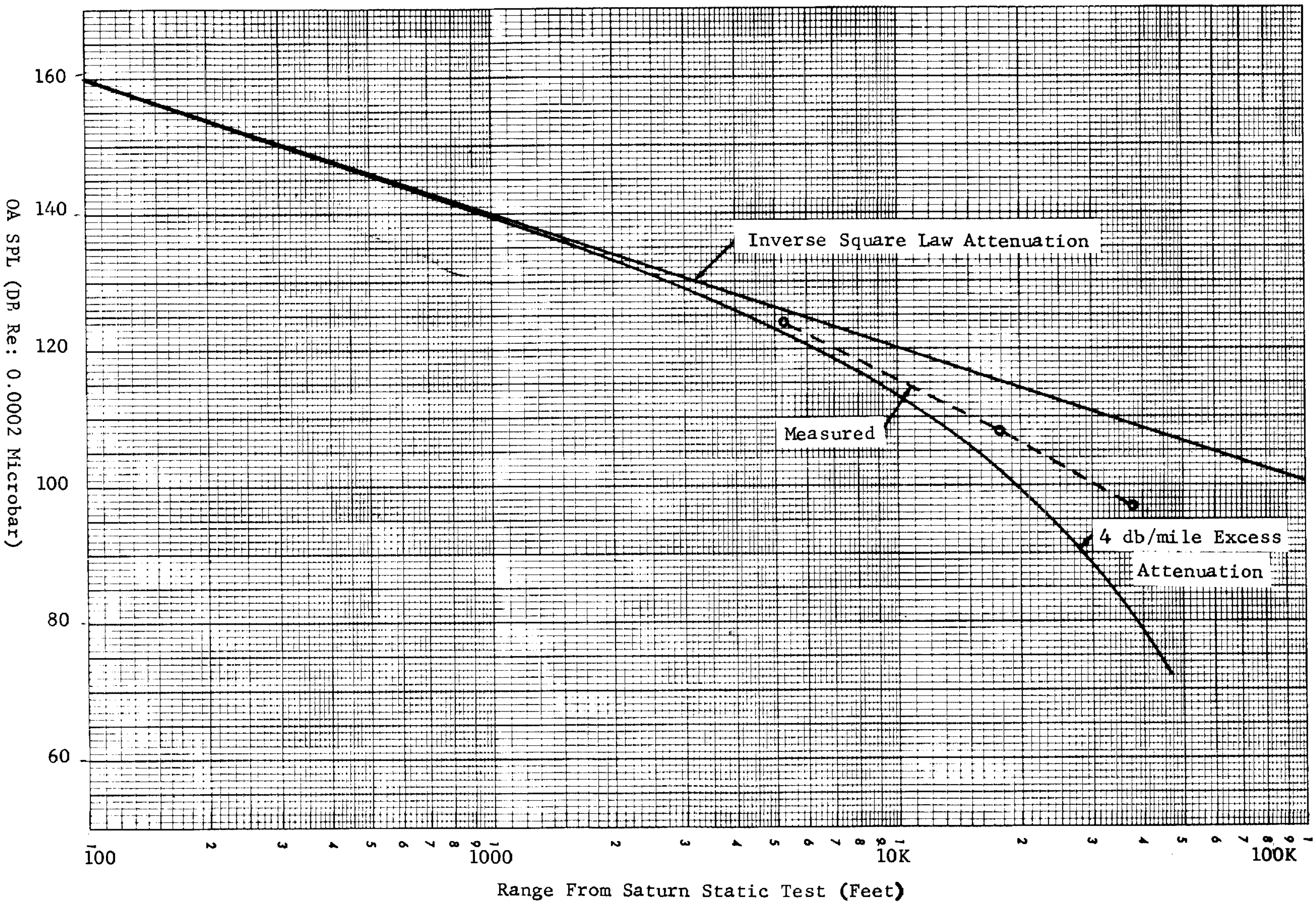


FIGURE 70. OVERALL SOUND PRESSURE LEVELS AT VARIOUS RANGES FROM SATURN TEST: SAT-20

Subsequent use of such a data presentation method has materially increased the accuracy with which the acoustic profiles are calculated.

It is thus possible to calculate, within the limitations of the available meteorological data, the boundaries of areas in which acoustical focusing is likely to occur. Such focusing, in the case of boosters of the Saturn class, resulted in increases in the sound pressure level of up to thirty decibels. By judicious monitoring of the meteorological parameters, it is possible to conduct large scale booster tests with no adverse community reaction.

Until recently, there existed very few sources of steady-state low frequency sound which were capable of high energy outputs. Generally speaking, the larger missiles and space vehicles were the only such audio generators. Since factors other than sound propagation usually determine the scheduling of these costly tests, the gathering of useful far-field acoustic data from them has been extremely slow. Therefore, the determination of the accuracy and reliability of the meteorological forecast techniques and the focal zone calculations has remained, until recently, largely a hit-or-miss proposition. Since the lack of proven techniques of this sort has itself somewhat restricted test scheduling, the problem has been largely self-sustaining.

However, MSFC's Test Division has now built a new high-power low-frequency sound source which is both more versatile and less expensive than any rocket engine. Operating from compressed air, this facility which contains one of the world's largest free-field "loudspeakers" is capable of over 1000 watts of acoustic power. Since this energy is directed by an exponential horn toward whatever receiver may be designated, whereas the Saturn engine noise is relatively nondirectional, the output at a given far-field receiver is only 30 decibels below that from the Saturn. The horn is mounted on a tower (FIGURE 71) and is capable of being rotated in any direction. Thus, up-, down-, and cross-wind measurements may be made.

The transducer used is electro-pneumatic. That is, it uses an electrically directed moving coil to modulate a flow of compressed air. By exciting the coil with either pure tones or random noise, it is possible to vary the output of the horn. It is hoped to use the horn not only to measure the rise or fall of sound pressure levels due to various meteorological conditions but also to empirically ascertain the value of the atmospheric absorption coefficients for various low frequencies.

FIGURE 71. ACOUSTIC FACILITY TOWER WITH EXPONENTIAL HORN

SECTION IX. CONCLUSIONS AND RECOMMENDATIONS

Experiments with the noise resulting from static test firings of the Saturn vehicle has demonstrated the need for a better understanding of factors affecting the long range propagation of sound. However, even with existing techniques in the fields of atmospheric physics and meteorology, it is possible to materially improve the chances of testing under conditions which will result in a minimum of acoustic energy reaching sensitive areas. The refinement and extension of the techniques presented in this paper should improve the reliability of such forecasts and will allow test personnel to take greater advantage of short periods of good weather.

With suitable modification, the rawinsonde observation system is capable of providing the requisite meteorological data for short period forecasts of sound propagation characteristics. Minor changes can be made in the balloon borne flight unit to increase its temperature sensitivity over the 10,000-foot altitude range. The studies indicate that slower ascent rates of 500 feet per minute or less would permit reduction of the effects of time lag in the thermistor and to permit valid use of smaller height intervals for more sensitive determinations of the wind profile. Ground tracking of rawinsonde flights by two GMD-1 units would improve the basic accuracy of the calculated winds. Under circumstances where double GMD-1 tracking is not feasible, a double theodolite system could be installed for supplementary wind observations during periods of critical meteorological conditions. Although cloud conditions do impose an altitude limitation, double theodolite observations can usually be made up to 2 to 3000 feet during most operational situations. If slow ascent rates are used, very accurate and detailed wind information can be obtained.

Preliminary, studies in sound ray propagation using digital computers have been valuable in studying the effects of changes in two-layer profiles of sound velocity. The boundaries of layers subject to meteorological focusing of the acoustic energy have been theoretically determined and field measurements have generally borne out the predictions. A possible extension of this work could be carried out to develop more specific mathematical relationships and computer programs for determining sound pressure levels within the focal areas. In addition, probable limits of uncertainty in the location and intensity parameters can be developed which would establish calculated risk values as a basis for more objective decision making.

The effects of range and terrain upon the assumption of a horizontally stratified atmosphere are presently unknown and specialized studies of these factors could be undertaken to examine their possible effects upon the larger meteorological environment and the resultant patterns of sound

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propagation. Also because of the rocket exhaust, the meteorological conditions surrounding the source (or sources) of such noise are considerably different from those usually assumed in the mathematical models. Therefore, studies are underway to ascertain these effects and to conclusively estimate the possible influences on the long range propagation of rocket noise.

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NASA-Langley, 1962

NASA TN D-1277
National Aeronautics and Space Administration.
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Richard N. Tedrick, Roy Peterson, T. Kleffman,
Wade D. Dorland, R. Ewing, and D. Church.
August 1962. 127p. OTS price, $2.75.
(NASA TECHNICAL NOTE D-1277)

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